# Loss of Life, Evacuation and Emergency Management

## Comparison and application to case studies in the USA

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# 1 Introduction

## 1.1 Background

Both in the USA and in the Netherlands extensive studies on approaches for identifying flood risks- the combination of levee failure probabilities and consequences -are ongoing. The outcomes of these methods will provide a better insight in the actual level of risk and contribute to a better and more cost and time efficient prioritization of risk reduction actions.  In recent years there has been a lot of information exchanged between experts from the Netherlands and the USA on these topics, e.g. within the Memorandum of Understanding between USACE and Rijkswaterstaat and several other meetings in the US and the Netherlands.

One topic that has received a lot attention in recent years is the (estimation of) loss of life due flooding and the associated risks. Historical events, such as the 1953 flooding in the Netherlands and the flooding of New Orleans due to hurricane Katrina, have demonstrated that life loss can be significant. Both in the US methods have been developed to estimate these consequences, and in both countries life loss will be considered in (future) policies and decision-making. It is therefore important that credible and reliable methods are available to analyse this type of consequences. Various methods have been developed in the Netherlands, US and other countries for various fields of application such as levee failure, dam breaching and tsunamis. Although these methods provide first insights in the range of loss of life that could be expected, there are still a lot of questions related to the empirical foundation of these methods and their application for policy decisions.

A related topic concerns evacuation and emergency management (EEM). The risks to life are directly influenced by the effectiveness of EEM. One challenge is to improve estimates of and insights in evacuation effectiveness, based on empirical data and the joint research efforts of social scientists and more engineering related research.

## 1.2 Objectives and Scope

In recent years experts from the Netherlands and the US have exchanged knowledge and information on methods for loss of life due to levee and dam breaching. However, a case study in which various approaches for analyzing loss of life and EEM are rigorously compared has not yet been executed.

Therefore, the first and main objective of this study is to compare Dutch and American methods for the analysis of loss of life and evacuation for a number of case studies in the US. This is referred to as the comparison effort in the remainder of this report.

A second, additional objective is to explore how approaches for analysis of risk to life and EEM that have been recently developed in the Netherlands, can be applied in the United States.

Overall, it is the aim of the research efforts in this project to contribute to the improvement of methods for loss of life estimation, risk assessment and emergency management, in the Netherlands, the US and other countries.

The scope of this report is limited to methods developed in the Netherlands and methods developed by USACE (HEC FIA and Lifesim). However, the approach in the comparison effort has been chosen in such a way that other methods can be added to the analysis in a relatively easily in the future.

The analyses and cases in this report mainly focus on larger-scale floods due to levee failure. Other types of floods, such as dam breaching and flash floods, have not been directly considered as part of the case studies, but can be part of future investigation.

## 1.3 Report outline

The report is structured as follows. Section 2 gives a general overview and qualitative comparison of methods for loss of life estimation and evacuation analysis that have been developed in the Netherlands and the United States.

A number of case studies have been selected as part of the comparison effort. These include the Natomas Basin (section 3) and the Herbert Hoover Dike (section 4). In these sections first the results obtained with the various loss of life and evacuation models have been compared. In the final parts of these sections some additional and more exploratory analyses have been added to investigate the application of new concepts for risk analysis and evacuation decision-making support, e.g. by means of the Evacuaid model.

As a third case study the case of New Orleans has been investigated (section 5). A number of datasets that provide more information on life loss, building damage and flooding during Katrina have been summarized, as a basis for the model comparison effort for the case of Katrina.

In the final section 6, a synthesis of main findings is provided and recommendations related to future research, applications and the development of best practices for loss of life estimation and risk analysis.

## 1.4 Acknowledements

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Part of this project has been supported by the Dutch innovation and research program Flood Control 2015.

# 2 Methods for loss of life and evacuation analysis

The first paragraph of this section (2.1) gives a general introduction to some of the concepts and definition used in loss of life modeling. In the remainder of this chapter a further explanation and comparison is included of methods for loss of life estimation (section 2.2) and evacuation analysis (section 2.3) that are used in the Netherlands and the United States.

## 2.1 General introduction

### 2.1.1 General

The loss of life due to flooding is one of the most important types of consequences. Several methods have been developed to estimate the number of lives lost due to flooding. These models can be used for different purposes, such as the support of policy and engineering design decisions that are related to (acceptable) flood risk and to provide information to planners and emergency managers to improve and optimize their strategies.

Examples of loss of life models are the empirical method developed for storm surge flooding in the Netherlands (Jonkman, 2007), the flood risks to people approach developed in the UK (Penning Rowsell et al., 2005), models developed for levee and dam breach flooding in the US (HEC FIA and Lifesim) and agent based models, such as BC Hydro's LSM, that give a detailed simulation of flooding and people movement and behaviour. More comprehensive overviews and discussions of the various methods are included in (Jonkman, 2007; Jonkman et al., 2008, di Mauro et et al., 2012).

A general characterization of various models is shown in Figure 1 with respect to their level of detail and modeling principles. The level of detail (vertical axis) varies from the modeling of each individual's fate to an overall estimate for the whole event. On the horizontal axis the basic modeling principles are categorized. Mechanistic models are those that model the individual behaviour and the causes of death. Empirical models relate mortality in the exposed population to event characteristics.

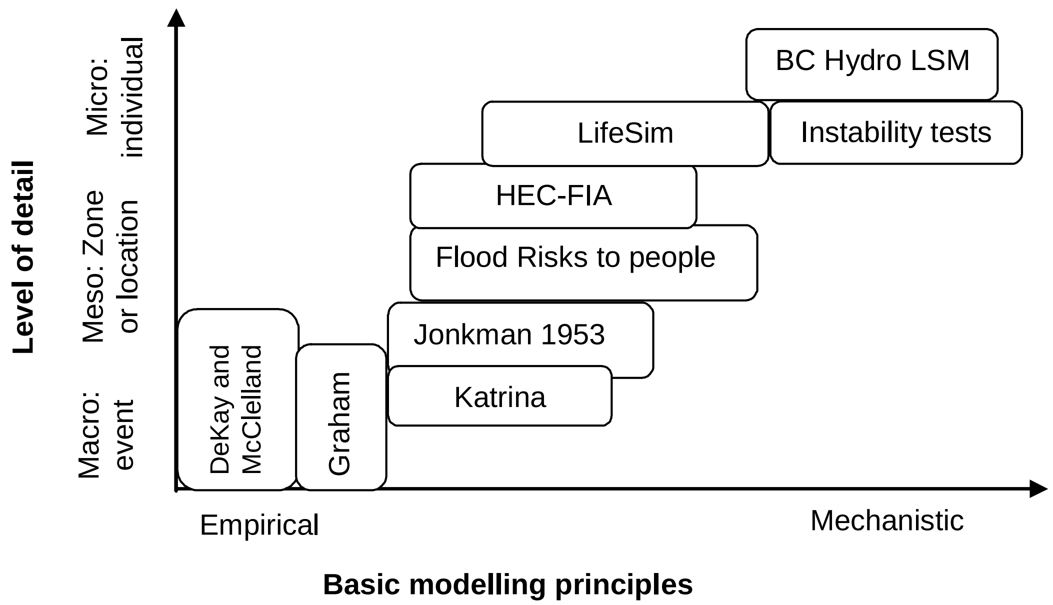



**Figure 1: Comparison of loss of life models (based on Johnstone *et al.*, 2005).**

### 2.1.2 Loss of life estimation and evacuation analysis

Estimation of the loss of life requires insight in a number of variables and elements that can be clarified based on the formula below (Jonkman, 2007):

$$N = F_d(1 - F_E)N_{PAR} \qquad (1)$$

Where:

N – loss of life estimate; $F_d$ – mortality fraction; $F_E$ – evacuation fraction (also evacuation effectiveness), $N_{PAR}$ – number of people at risk.

The mortality fraction ($F_d$) expresses the ratio between the number of people killed and the number of people exposed in the floodzone, i.e. those present when the water arrives. Note that a different definition is used in the USBR's DSO-99-06 method (Graham, 1999). There, the fatality rate is defined as

*Fatality rate = Loss of life / People at Risk = N / $N_{PAR}$* *(2)*

This definition implies that evacuation effectiveness does not directly influence the fatality rate.

The mortality is generally expressed as a function of flood characteristics, such as depth, flow velocity and rise rate, and outputs of hydrodynamic flood simulations are generally used to estimate these parameters. In some models mortality is also related to structural building performance in flood loads. Some models, e.g. the models used in the Netherlands, apply one mortality rate to all people in an affected region, irrespective of the state that they are in. Other models, e.g. Lifesim, make a distinction of the various states that people can be in, e.g. in a building or car, and assign different mortality fractions to these groups.

To come to an adequate estimate of loss of life the effectiveness of evacuation fraction or evacuation fraction ($F_E$) is a key parameter. For example changing the evacuation effectiveness from 0.5 (50%) to 0.9 will reduce the life loss by a factor of 5, and changing it from 0.5 to 0.98 by a factor of 25. In the Dutch practice evacuation is defined as movement to a safe location outside the floodzone before the flooding or breaching starts. In the American practice, also evacuation and movement after breaching is considered.

In addition to evacuation out of the area, shelter in a safe location within the area can be considered. The effectiveness of shelter can be included in separate term in equation 1 (the shelter fraction) or it can be indirectly reflected in the mortality fraction.

Finally, the number of people at risk ($N_{PAR}$) in the floodzone has to be identified. An estimate can be based on population data, and the number of people present during certain times of the day and the year.

## 2.2 Methods for loss of life estimation

In this section the methods for analysis of loss of life that are used in the Netherlands and United States are compared. The contents of this section mainly focus on the estimation of the mortality fraction.

### 2.2.1 Approaches based on the 1953 flood in the Netherlands

In the PhD thesis of Jonkman (2007) a method has been proposed for the estimation of loss of life due to floods. It is applicable to low-lying areas protected flood defences and specifically focuses on large-scale flooding due breaching of flood defences due to river and coastal flooding.

The mortality functions have been derived based on data from the 1953 storm surge disaster in the Netherlands (1853 fatalities), UK (315 fatalities). Additional data from storm surge flooding in Japan during Isewan Typhoon in 1959 (5100 fatalities) has been added to the analysis.

Based on the observations from these historical floods, three typical zones with different mortality patterns have been distinguished (see also Figure 2):

- **Breach zone:** Due to the inflow through the breach in a flood defence high flow velocities generally occur behind the breach. This leads to collapse of buildings and instability of people standing in the flow.
- **Zones with rapidly rising waters:** Due to the rapid rising of the water people are not able to reach shelter on higher grounds or higher floors of buildings. This is particularly hazardous in combination with larger water depths.
- **Remaining zone**: In this zone the flood conditions are more slow-onset, offering better possibilities to find shelter. Fatalities may occur amongst those that did not find shelter, or due to adverse health conditions associated with extended exposure of those in shelters.

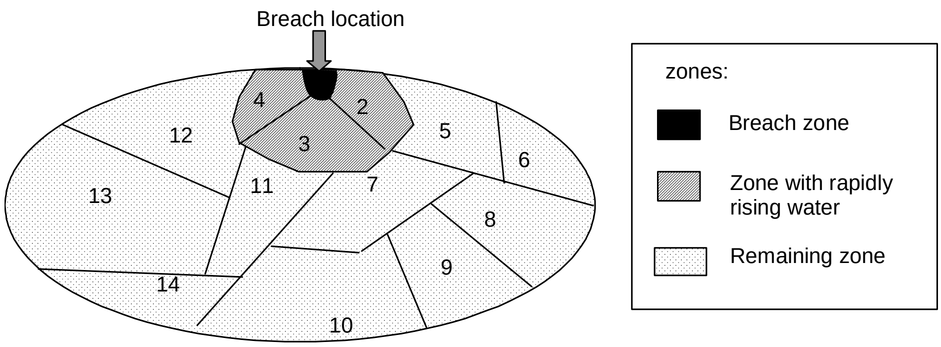



Figure 2: Zones in mortality estimation (Jonkman, 2007).

These zones are based on typical flow patterns after levee failure. For other types of floods, the situation and proportional area of the hazard zones might be different. For example for dam breaks in narrow canyons, the hazard zone associated with high flow velocities will be much larger.

For every zone a mortality criterion has been proposed. For the breach zone, no empirical data to calibrate the relationship between flow velocities and life loss was available. Therefore, a criterion has been proposed based on studies on building collapse. It is assumed that mortality equals $F_d$=1 (i.e. 100%) if the combination of the combination of depth (d [m]) and velocity (v [m/s]) exceeds dv=7m/s$^2$.

For the other two zones mortality functions have been developed based on the historical data. Figure 3 and Figure 4 show the mortality functions for the zone with rapidly rising water and the remaining zone. The two mortality functions explicitly include the effects of water depth. The numerical value of the rise determines which of the two functions has to be used and a threshold value of 0.5 m/hr was proposed. The function for the zone with rapidly rising water gives a good fit with the observed data and shows that mortality increases rapidly when the water depth increases. One uncertainty is the course of the function for larger water depths, as no direct empirical data is available to calibrate the trendline for these conditions. The bestfit trendline for the remaining zone is less adequate. For these observations the effects of warning and other factors, such as water temperature, preparedness and population vulnerability could be relevant

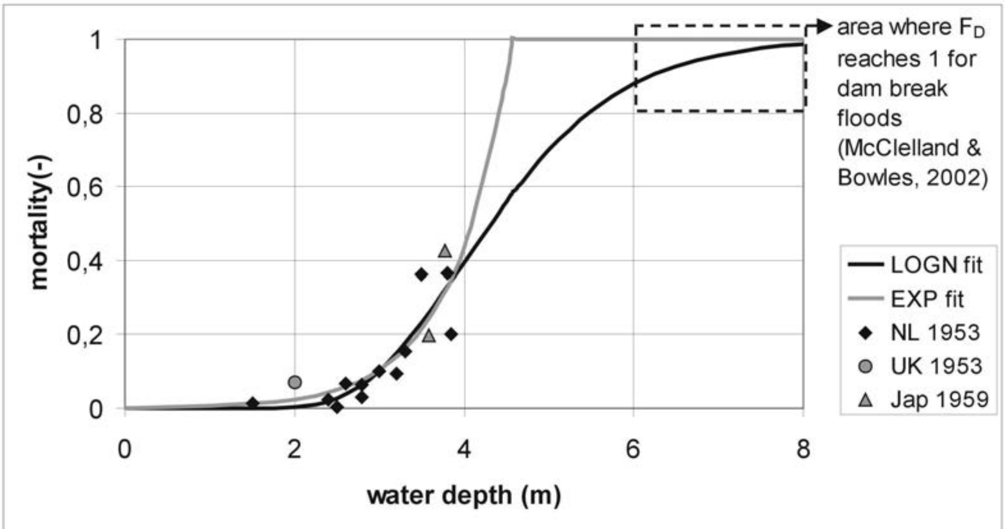



**Figure 3: Mortality function for the zone with rapidly rising water (Jonkman, 2007)**

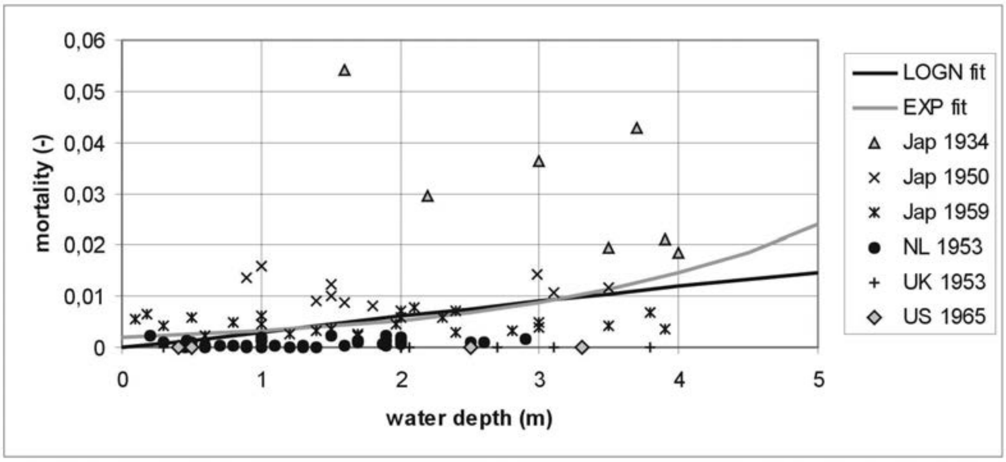



**Figure 4**: Mortality function for the remaining zone (Jonkman, 2007)

**Interpolated 1953 mortality functions**

In a later revision of the method (Maaskant et al., 2009) the effect of the rise rate on mortality has been modified in the method based on the 1953 disaster. The rationale for the modification was that it appeared that there could be a very sudden jump in mortality if the threshold for the rise rate value of 0.5 m/hr was exceeded, especially in combination with larger water depths. It also appeared

that the data of the 1953 storm surge did not give a very clear indication of what the critical threshold for rise rate would be. Based on the re-consideration of the rise rate information of 1953 and practical consideration it has been proposed to interpolate the mortality functions for rise rates between 0.5 m/hr and 4 m/hr. This effect is shown in the figure below and this area is labelled the transition zone. This function is currently implemented in the standard methods for consequence assessment (HISSSM) in the Netherlands, and will therefore be used for further reference and comparison below.

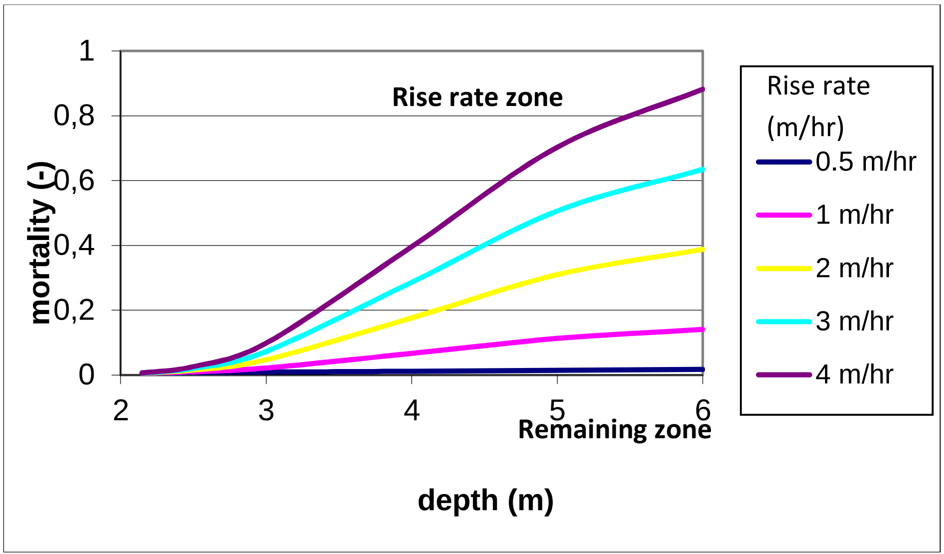



Figure 5: Interpolated mortality functions based on the 1953 disaster (Maaskant et al., 2009).

The complete set of equations for the method based on the 1953 flood disaster is included in appendix 8.1.

### 2.2.2 New Orleans / Katrina mortality functions

Hurricane Katrina struck New Orleans and the Gulf coast in the year 2005. This tragic disaster led to enormous destruction and more than 1100 fatalities, but it was also an important opportunity to learn and analyze the causes and consequences of failure.

A preliminary dataset that gives information on the recovery locations and individual characteristics for 771 fatalities has been analysed, see Jonkman et al., 2009, Maaskant, 2007, Brunkard *et al.,* 2008 and Boyd, 2011, for further background. Figure 6 gives an overview of the spatial distribution of recoveries in and near the flooded parts of New Orleans. A distinction is made between two categories of fatalities:

1. Recoveries from residential locations such as residences, nursing homes, street locations and public buildings. Fatalities in these facilities can often be directly related to the flood effects.
2. Recoveries from medical locations, shelters and morgues / funeral homes. These recovery locations indicate that these fatalities were not directly related to the impacts of floodwaters.

One third of the analysed fatalities occurred outside the flooded areas or in hospitals and shelters in the flooded area. These fatalities were due to the adverse public health situation that developed after the floods. Two thirds of the analysed fatalities were most likely associated with the direct

physical impacts of the flood and mostly caused by drowning. The majority of victims were elderly: nearly 60% of fatalities were over 65 years.

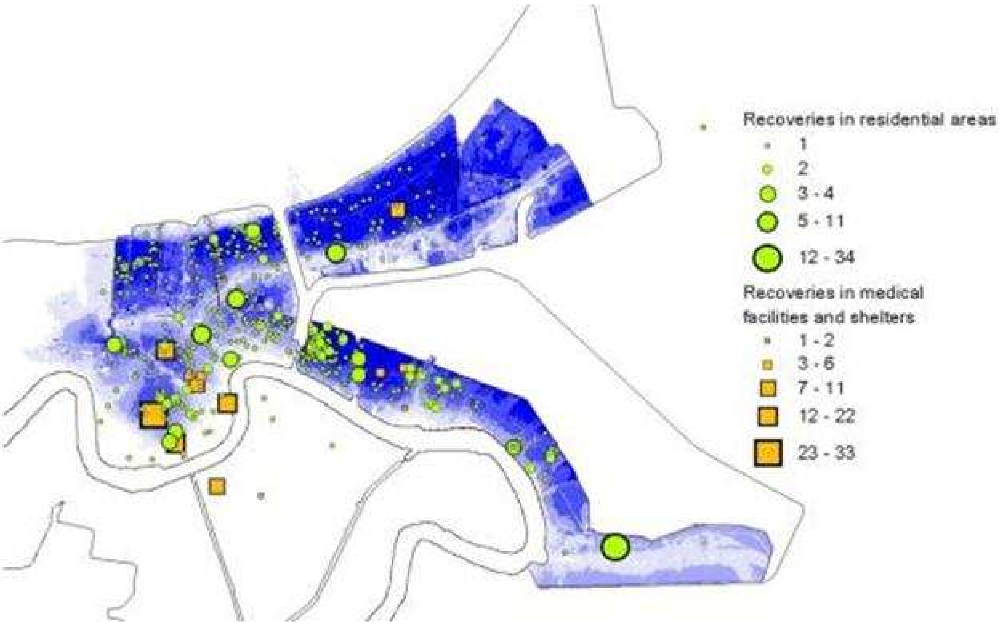



**Figure 6: Recovery locations and flooded area (Jonkman et al., 2009)**

The consequences of the flooding of New Orleans were relatively well-documented and these data provide additional insight in the relationship between flood characteristics and mortality. Based on the outputs of flood simulations the relationship between the mortality and various flood characteristics (depth, velocity, rise rate) has been investigated.

The analysis has been done at the neighbourhood level. In total 437,500 people lived in the flooded area in New Orleans. It is assumed that 10% of the population was exposed, since the evacuation rate was assumed to be 80% based on traffic counts and a shelter rate of 10% was assumed (see Jonkman et al., 2009 for further details). Overall, it was found that mortality rates were relatively high in the areas with large water depths and areas directly behind breaches (Jonkman *et al.*, 2009). The overall mortality amongst the exposed population for this event was approximately 1%, which is similar to findings for other historical coastal flood events (Jonkman, 2007).

The analysis showed that the rise rate did not have a significant effect on the mortality. There appeared to be some relationship ($R^2$=0.42) between the flood depth and mortality in the metro and St. Bernard bowls, see Figure 7.

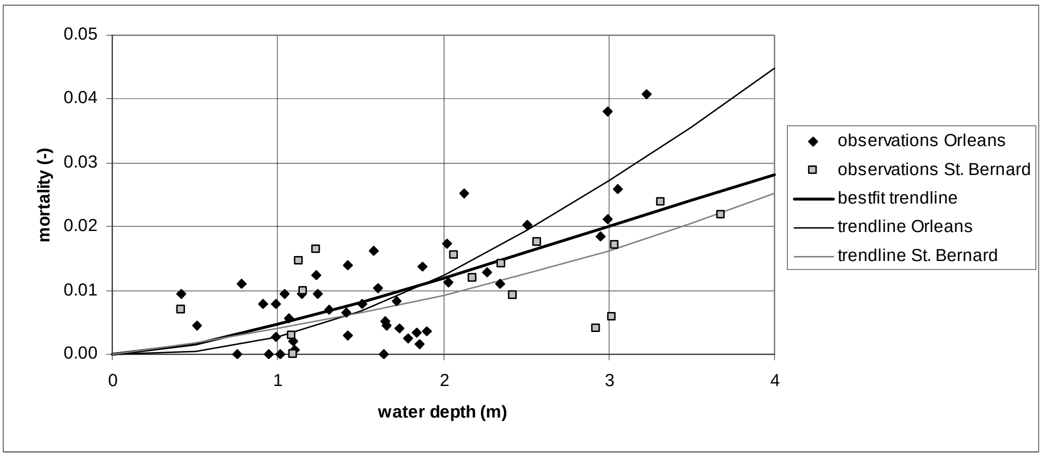



**Figure 7: Relationship between water depth and mortality for the Orleans and St. Bernard bowls.**

A large number of fatalities (73) occurred in the neighbourhood the Lower 9th Ward. This neighbourhood is located next to the two large breaches in the Industrial Canal levees. Various eyewitness accounts tell how the floodwater entered this neighbourhood through the breaches with great force and how it caused death and destruction in the areas near the breaches. Based on the flood simulations and building damage observations (Pistrika and Jonkman, 2009) it was found that higher mortality (Fd>0.05) occurred in areas where dv>5m2/s.

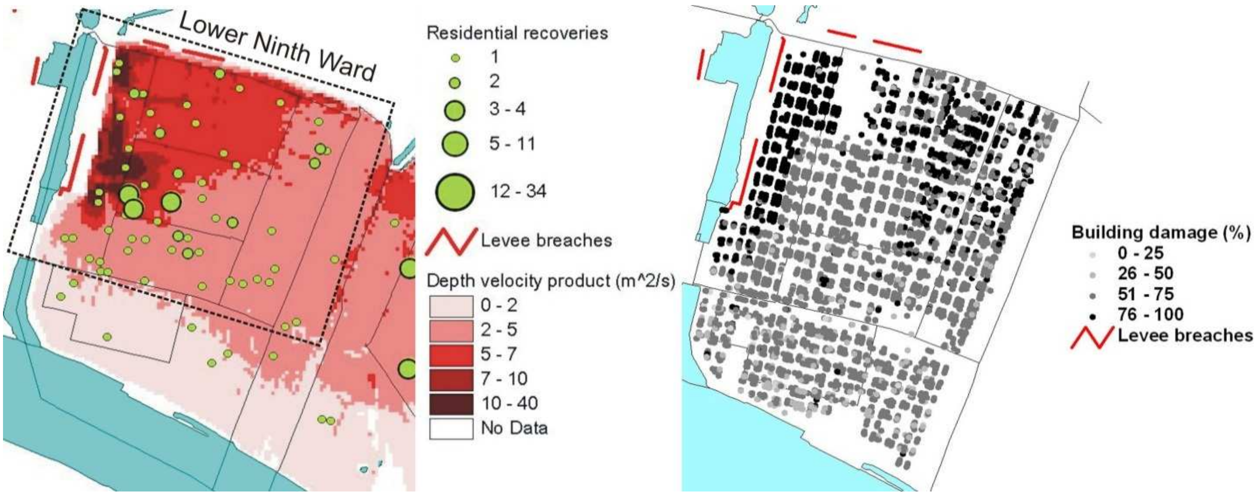



**Figure 8: Spatial distribution of the recovered fatalities and the depth-velocity product for the Lower 9th Ward (left) and building damage levels (right - source: http://www.unifiedneworleansplan.com/home2/section/24, accessed December 2006. Damage levels determined in post Katrina damage assessments conducted by the City of New Orleans and FEMA).**

The approach for mortality estimation that follows from hurricane Katrina is summarized in Figure 9 below. The main difference with the method derived based on the 1953 disaster is that a) no effect of rise rate is found in the Katrina data; b) the mortality in the breach zone (5 – 10%) is much lower than assumed in the 1953 method (100%). When the 1953 method is applied to Katrina the number of fatalities is over predicted but within a factor 2. When both methods are applied to case studies in the Netherlands, the deviation in outcomes is relatively small and about 15% on average (Maaskant, 2007).

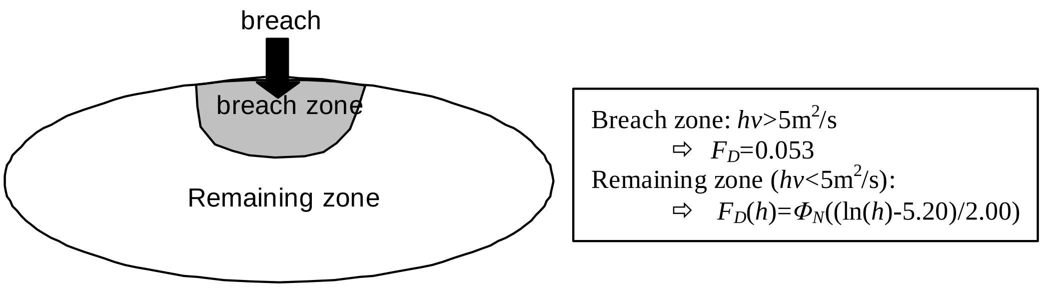



**Figure 9: Mortality functions and zones derived based on data for the flooding of New Orleans.**

### 2.2.3 HEC FIA methodology description

- Brief description of the model

  HEC-FIA is a single event geospatially based model that calculates life loss and economic losses. The software can be used for rapid assessments of life loss at a rough level, but is very scalable to allow users to modify inputs and parameters to accurately describe the floodplain and the geospatial location of the population to get much better results for alternative analysis. HEC-FIA attempts to model the full progression of the flood wave with as little data as necessary, and the response of individuals to warnings and the flood wave. From the hydraulic inputs HEC-FIA looks at how well the structures and individuals survive based on their ending location and exposure to the hazard. HEC-FIA is a standalone program that can be run from a personal computer that is not connected to the internet. There is potential for significant GIS pre-processing for the structure inventory or other elements describing the floodplain, and hydraulic modeling

- Hydraulic inputs

  HEC-FIA accepts information from multiple hydraulic model types, it can accept 2D model output in the form of grids (ascii, flt, or TMS), or it can bring in 1D hydraulic data via hydrographs at individual cross sections, or grids. For life loss the minimum required inputs are the arrival of water (2ft is default) and maximum depth achieved for each gridcell,. If more detailed analysis is desired, the maximum of depth times velocity across the modeled time for each gridcell can be provided to determine the impacts of velocity on life loss.

- Population/structure inventory

  HEC-FIA uses a geospatially based methodology to describe the built inventory. Structures are defined as points on a map for x and y location, and have their z value or elevation determined by a digital elevation map (DEM). Structures can be added into HEC-FIA through many different methodologies, by point shape file (for surveyed structures), parcel data (if geospatial data describing the location of the parcels), or from the HAZUS database. The structure inventory is described by a series of attributes, damage category allows the user to aggregate like structures together (residential, commercial, industrial), occupancy type allows the user to specify differences within a damage category (residential with or without basements, multiple stories, multiple family dwellings, masonry or wooden etc.), foundation heights, values, and population. The most rapid way of generating a structure inventory is to use the HAZUS database. The HAZUS database is a product generated by FEMA that represents the entire United States at the

state, county, tract and census block level. The data represented consists of structures and characteristics about those structures, and population and characteristics of the population, the smallest geographic representation is the census block. HEC-FIA accesses the data at the census block level, extracts relevant information and creates a uniform grid based on structure density and creates individual structures at the vertices of the grid within the census block. FIA then distributes the population within the structure inventory based on building type. The building type is correlated to a quantity of households. (see figure 1) FIA then calculates the population for both day and night, and the proportion of the population that is over or under 65 for those two times of day(eq. 1) Once the total number of people is determined by census block it is divided by the total number of households, and then each structure receives the number of people based on how many households it contains. This process is intended to determine the population exposed during the day and the night since the population moves in and out or to different locations within the floodplain based on time of day. The HAZUS data is based on the US CENSUS and since that is only conducted once every ten years the population data can be inaccurate, to facilitate the process of updating that information HEC-FIA allows the user to define regions where population has fluctuated and by how much it has fluctuated to more accurately describe the exposed population. As part of the HEC FIA method the warning, mobilization and evacuation of the population are analyzed. The method is described more in detail in section 2.3.4.

- Assigning Fatality rates

From the warning process, evacuation outcomes are determined based on the arrival of 2 ft of water at the structure and the location they are evacuating to. These outcomes are either **cleared**, in that they reached the safe location prior to the water, **caught**, in that they evacuated from their structure but were caught along the way, and **not mobilized**, in that they either decided not to mobilize or were unable to given the arrival time of the water.

**Cleared**: the people that evacuate safely do not receive a flood lethality zone assignment.

**Caught**: the people that get caught evacuating are assigned to the Chance Zone.

**Not mobilized**: the people that stay in structures are assigned to flood lethality zones based on maximum instantaneous depth times velocity, maximum depth of flooding over the entire flood event and the height of the structure. The assumption in Simplified LIFESim is that people evacuate to the level above the highest habitable level in the structure (e.g. the roof or an attic).

a) For any structure: if the depth times velocity exceeds the RESCDam criteria for partial survivorship, the structure will receive either chance or compromised given maximum depth, if the depth times velocity exceeds the RESCDam criteria for total destruction, the category is automatically determined to be Chance.
b) For any structure: if structure totally survives and event maximum depth < 2 feet or less than the foundation height (fh) of structure, then no flood lethality zone assignment is made and the people are grouped with the Cleared evacuation category;
c) If 1-story structure where the population is under 65:

i) if the structure totally survives and event maximum depth < fh + 13 feet then assign to Safe Zone, if structure partially survives, and maximum depth < fh +13 ft then assign to compromised zone, if structure is totally destroyed, then assign to chance zone:

ii) if the structure totally survives or partially survives the event and event maximum depth ≥ fh + 13 feet and < fh + 15 feet then assign to a Compromised Zone, if the structure is totally destroyed, then assign to chance zone;

iii) else event maximum depth ≥ fh + 15 feet then assign to a Chance Zone.

For each additional story, add 9 feet to the depth criteria in c) to determine flood lethality zone. Depending on occupancy type the fatality rates for over 65 the lethality zone thresholds can be set lower.

Once the lethality zone is determined by each structure HEC-FIA applies the following average fatality rates based on the probability distributions of fatality rates for each Flood Lethality Zone described by McClelland and Bowles, 2002. The lethality zones are intended to describe the environment at the time of the flood, and the probability of survivorship given that environment, general descriptions of the zones and associated fatality rates are shown below.

a) *Chance Zones*: in which flood victims are typically swept downstream or trapped underwater, and survival depends largely on chance; that is, the apparently random occurrence of floating debris that can be clung to, getting washed to shore, or otherwise finding refuge safely. The historical fatality rate in Chance Zones ranges from about 38 percent to 100 percent, with an average rate over 91 percent.
b) *Compromised Zones:* in which the available shelter has been severely damaged by the flood, increasing the exposure of flood victims to violent floodwaters. An example might be when the front of a house is torn away, exposing the rooms inside to flooding. The historical fatality rate in Compromised Zones ranges from zero to about 50 percent, with an average rate near 12 percent.
c) *Safe Zones*: which are typically dry, exposed to relatively quiescent floodwaters, or exposed to shallow flooding unlikely to sweep people off their feet. Depending on the nature of the flood, examples might include the second floor of residences and sheltered backwater regions. Fatality rate in Safe Zones is virtually zero and averages 0.02 percent.

   The entire probability distributions of fatality rates for each Flood Lethality Zone are used in HEC-FIA when the uncertainty analysis option is selected

**Strengths/Weaknesses**

HEC-FIA attempts to take into account age, warning methodology, daily activity, effectiveness of warnings, vertical evacuation, and the dynamic nature of the flood. The strengths of this approach are the capability of distinguishing between geographic locations, population characteristics, warning system types and the built environment. Having the full floodwave described in a few summary grids helps HEC-FIA reduce the data to a minimal amount without losing the specificity of the hydraulic event. HEC-FIA has limitations when approaching the evacuation portion of the life loss equation. If there is a significant issue associated with traffic jams or the interaction of the population with the

floodwave during evacuation, HEC-FIA may underestimate the life loss in the category of caught evacuating.

**Conclusion**

HEC-FIA is a program that quickly assesses the potential for life loss of flood events, and gives insight into potential improvements within the flood plain either structural or nonstructural that can reduce the life loss potential. HEC-FIA may not be able to accurately portray the evacuation model, but it gives the user general information about the overall risk within the flood plain and is sufficient for most cases. A qualitative assessment of issues can be used to influence the modelers description of the consequence for a given event.

### 2.2.4 Loss of life methods comparison and discussion

**General comparison**

A comprehensive comparison of the various modeling approaches is included in Table 1 below.

| | 1953, and 1953 interpolated | Katrina | HEC FIA | Lifesim |
|---|---|---|---|---|
| Application: flood types | Levee breaching, river, coastal | Levee breaching, river, coastal | levee breaching, dam failure | levee breaching, dam failure |
| Application | Regional and national risk assessment | Regional and national risk assessment | Planning purposes | Planning &More detailed analysis |
| Implemented | HISSSM standard tool in the NL | (used in levee screening tool?) | HEC-FIA | Lifesim |
| **Inputs** | | | | |
| Population data | Inhabitants | Inhabitants | Day or night population | Day or night population |
| Main hydraulic Input data* | d, v, w | d, v | d, v, w, t | d, v , w, t |
| Building vulnerability / shelter | - (building indirectly in breach zone) | - (indirectly in breach zone) | Degree of shelter included | Degree of shelter included |
| Shelter | Can be included as a separate fraction | Can be included as a separate fraction | Degree of shelter is included | Degree of shelter is included |
| Evacuation concept | Evacuation before flood considered, given as input fraction | Evacuation before flood considered, given as input fraction | Includes warning and evacuation routine before and during a flood. | Includes warning and evacuation routine, incl road network before and during a flood |
| Scale of input data | Larger-scale (dike ring) population distribution | Larger-scale (dike ring) population distribution | Individual structure level | Individual structures |
| **Model concept** | | | | |
| Type of modelling | Static, empirical | Static, empirical | Static, based on distribution of people over zones | Dynamic |
| Empirical basis | 1953 Netherlands UK, 1959 flood in Japan | 2005, Katrina New Orleans | Derived from Lifesim | Various dam break floods |

| | | | | |
|---|---|---|---|---|
| Method: zones and states | four zones: breach, rapid rise, transition, remaining | Two zones: Breach, other | 3 states: cleared, evacuating and not mobilizes, with 3 criteria: safe, compromised, chance | Dynamic model Three states: safe, compromised, chance |
| Mortality rate calculation | Continuous functions | Continuous functions | Step-wise functions | Step-wise functions |
| Main reference(s) | Jonkman, 2007 Maaskant et al., 2009 | Jonkman et al., 2009 | USACE, 2011a | McClelland and Bowles, 1999, 2002; Aboelata, 2003 |

*d – flood depth, v – flow velocity; w – rise rate; t – arrival time

Table 1: Loss of life methods comparison

**Comparison of mortality functions**

The mortality functions that are implemented in the various methods are graphically compared below. The HEC-FIA functions have been shown for a single story residence. Two figures are shown for two domains of water depth. In the Dutch method no effect of the rise rate is included up to water depths of 2.1m and one mortality function is used. For higher water depths various functions are used depending on the rise rate.

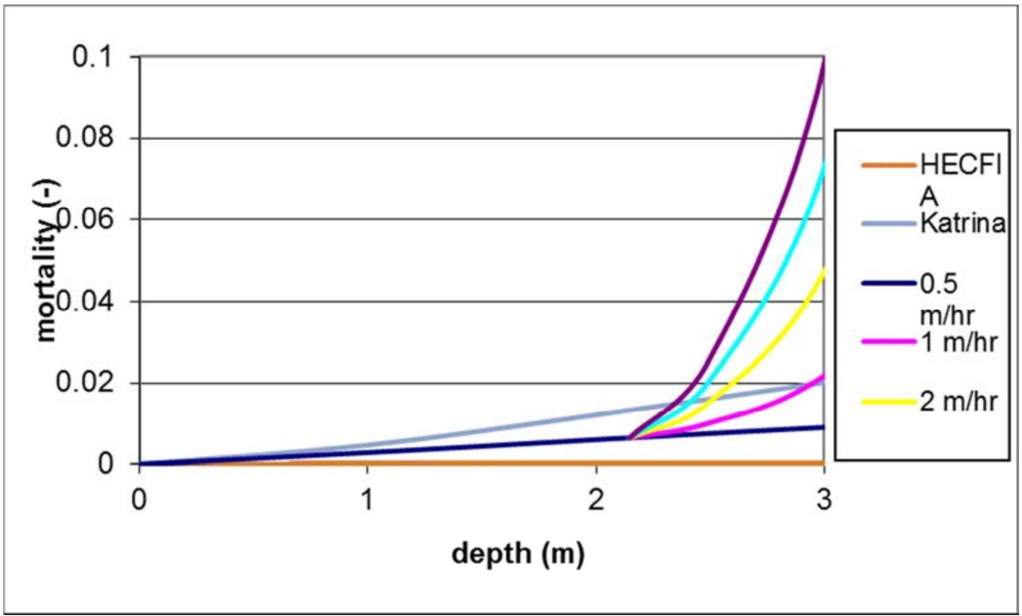



Figure 10: Comparison of the 1953 interpolated method, Katrina functions and HEC FIA for a single story residence (0-3 meter).

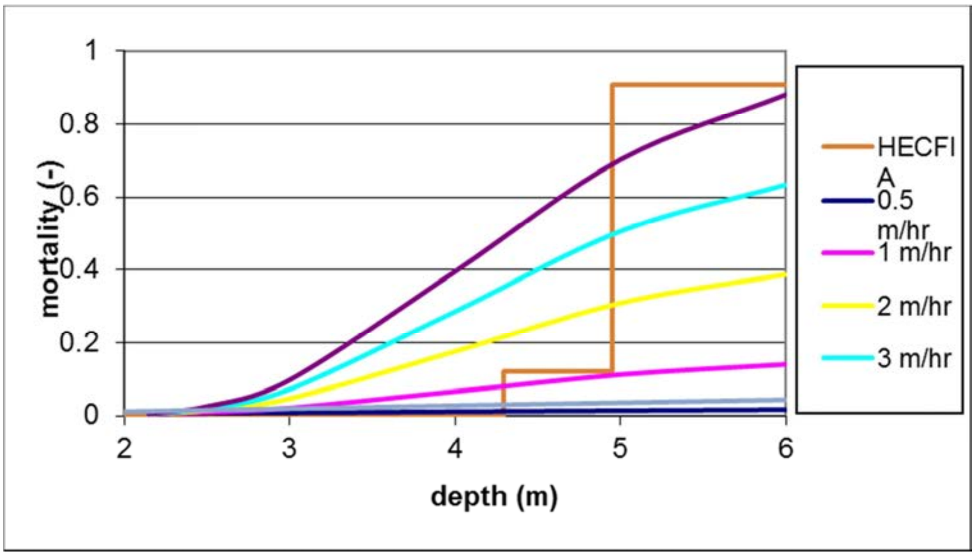



**Figure 11: Comparison of the 1953 interpolated method, Katrina functions and HEC FIA for a single story residence (2-6 meters).**

For water depths up to 2m the Katrina method gives the highest mortality rate prediction, higher than the interpolated 1953 and HEC FIA method.

HEC FIA estimates a mortality fraction of 0.0002 up to depths of 4.3m (13 ft) for people in a one story building. This is lower than the mortality fractions from the interpolated 1953 and Katrina functions. It is not a fully valid comparison since the 1953 and Katrina functions will be applied to all the people present in the area, whereas the low mortality rate in HEC FIA will only be applied to people in a building. In HEC FIA people can also be in another "state", for example evacuating, with a higher mortality rate.

For water depths higher than 2m, the interpolated 1953 functions for rise rates higher than 0.7m/hr give higher mortality fractions than the Katrina functions.

**Discussion**

The comparison of methods and mortality functions show that there are several differences between the models in terms of model framework, their empirical basis and the functional relationships that are applied. Therefore, it is firstly important to understand how the differences in outcomes between different models emerge. This can be done by applying them to hypothetical cases and flood scenarios as is demonstrated in the other sections of this report.

Also, it is highly relevant to "test" or validate the various models for actual floods that have occurred in the (recent) past. It is noted that it is important that these events are not part of the calibration or derivation dataset of the model.

For example, the Katrina loss of life dataset that has been documented in sections 2.2.2 and 5.2 of this report could be highly relevant for such a comparison. Another recent event with significant life loss was the flooding on the West coast of France due to storm Xynthia in the year 2010. This led to about 60 fatalities due to surge and flood effects. A recent validation effort (di Mauro and de Bruijn, 2012) focused on the Canvey Island case study.This island was flooded during the 1953 surge on the North Sea and about 60 fatalities occurred on the island.

## 2.3 Methods for evacuation

### 2.3.1 Introduction

Evacuation is defined as the organization and movement of (part of) the population to a (relatively) safe place in case of a threat (Kolen and Helsloot, 2012). Evacuation is a possible measure to reduce loss of life in case of a disaster or a threat of disaster. By evacuating, fewer people are exposed to the direct consequences of a disaster, provided that they can leave the area in time. If it is not possible to leave the area in time, people can reduce their vulnerability and risk of loss of life by moving to a relatively safe place such as a shelter or safe-haven. Four phases of preparation and decision making for evacuation can be defined:

- Phase 0: Planning and design. Available plans, experience, efficiency infrastructure and risk perception can improve the success of evacuation
- Phase 1: Detection and recognition (sense making) after early warning by decision makers and citizens
- Phase 2: Organization and decision-making by leaders and citizens (transition phase from normal life to an evacuation mode).
- Phase 3: Period of moving from one place to another including the process of warning and mobilization of the public after the evacuation decision has been made in phase 2.

In this section we focus on the time needed for removal of people prior to flooding during phase 3. This period includes the process of warning and mobilization after decisions are made to call for evacuation. Three different steps can be defined during the period of moving (phase 3):

- Departure: The combination of warning and mobilization which describes the number of people who start to travel as a function of time after a call for evacuation is made.
- Travel: The time needed to move from a place to another.
- Exit: The time needed to leave the evacuation zone.

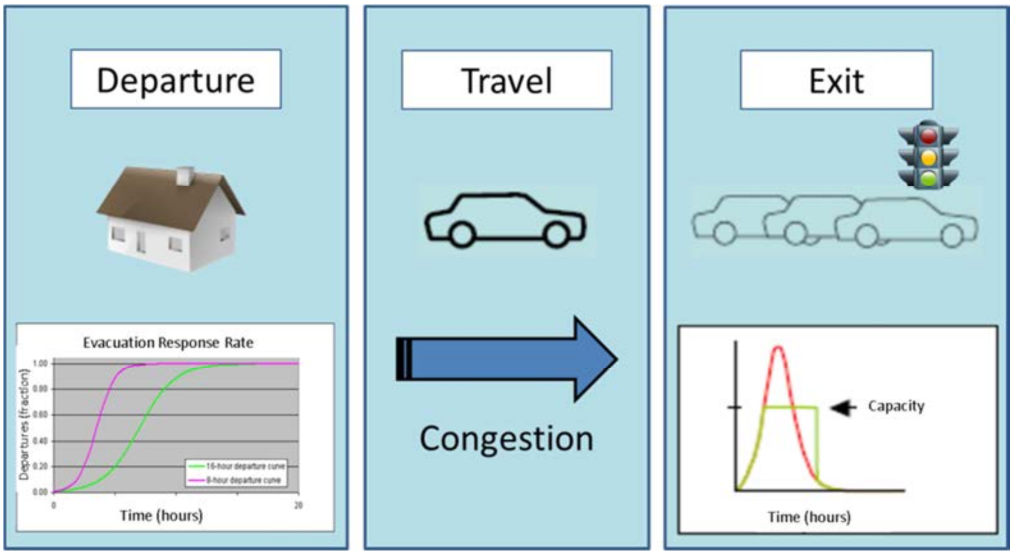



Figure 12: Process of evacuation is split in a process of departure, travel and exit.

### 2.3.2 Dutch Evacuation and EvacuAid approach

#### 2.3.2.1 *Evacuation analysis applied in the Netherlands (deterministic)*[1]

Triggered by the flooding of New Orleans caused by Hurricane Katrina, the Dutch government decided to enhance flood preparedness (Remkes, J. 2006). Criteria for the level of preparedness were however not defined. Emergency plans for flood prevention and large scale evacuation were as a result prepared by the national and regional authorities (Ministry of the Interior and Kingdom Relations, 2007; National Operational Centre, 2008; Ministry of Transport, Public Works and Water Management, 2008; Wegh, E., 2008; Brabant, Veiligheidsregio Midden- en West, 2008; Haaglanden, Hulpverleningsregio, 2008; Zeeland, Veiligheidsregio, 2008; Taskforce Management Flooding, 2009). This section describes the use of deterministic planning for evacuation and the application in The Netherlands for emergency planning, for the National Security Assessment and for a quantitative flood risk analysis in the Netherlands (VNK2). Most strategies focus on preventive evacuation (as in the emergency planning mentioned above and the VNK2 project). For the national security assessment also other strategies are taken into account which only evacuate people preventive in high risk areas and others remain in the area and evacuate vertical or shelter in place. This is because a complete preventive evacuation is not always possible. The same approach is applied for the UK East Coast flooding in Lincolnshire, Norfolk and Humber. Modeling, consequences and risk analysis in the Netherlands focus on preventive evacuation prior to flooding.

#### 2.3.2.2 *Modeling approach*

Scenarios for evacuation describe the evacuation process as a function of time based on boundary conditions as:

- Threatened area, people at risk and different risk zones in this area
- Road network and exit points
- Traffic management
- Non-compliance and departure curve (citizen response)

These are further discussed below.

***Threatened area, people and different risk zones in this area***

The threatened area is determined based on the combination of the possible flood scenarios prior to flooding, the forecasts and the actual circumstances of the levees (see Figure 13). Based on the characteristics of people in an area and the consequences of a possible flood, different zones are defined (using for example zip codes). These zones distinguish:

- A high and low threatened area based on the expected water depth and the chain of consequences outside the flood zone.
- People with special needs and people without these needs

[1] This section is based on Kolen, B. and Helsloot, I. (2012), Time needed to evacuate the Netherlands in the event of large-scale flooding: strategies and consequences. Disasters, 36: 700–722. doi: 10.1111/j.1467-7717.2012.01278.x

The population to be evacuated has been divided into groups of people based on zones (zip codes). About 11% of the total population is estimated to be unable to evacuate without requiring medical assistance and is not considered self-reliant; they will need the support of emergency services to evacuate (Statistical data Statline, 2008, National Care Atlas (Nationale zorgatlas), 2008. All other citizens are assumed to evacuate on their own, supported by family or other citizens, and are considered self-reliant.

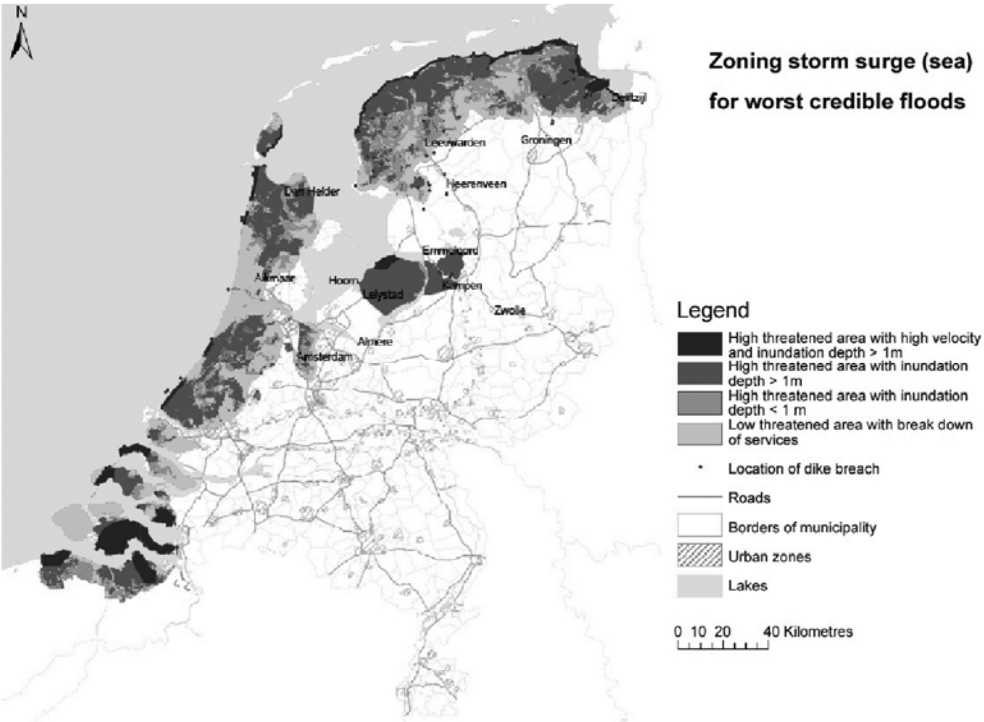



Figure 13: Threatened area in case of an extreme storm surge (Ministry of the Interior and Kingdom Relations, Ministry of Transport Public Works and Water Management, 2008).

### *Road network and exit points*

The evacuation model takes the most important routes into account. People are assumed to be safe when they arrive at an exit point. Such an exit point is defined as a location outside the threatened area in case of preventive evacuation. A reduction of the outflow is taken into account because of the conditions on the overall road network, like congestion. People within the threatened area are connected to the road network by connecting the centroid of the zone to the nearest road.

### *Traffic management*

Different forms of traffic management are used to consider optimistic and pessimistic scenarios, these traffic management types are part of the so called ‘evacuation calculator,’ of which a more detailed description is provided by Van Zuilekom et al., 2005. The traffic management strategies are:

- Reference situation: The evacuees from the “origin zones” (the areas where they originate) are distributed equally over all possible exit points. This strategy approaches a situation in which no direction is given in the evacuation process. Crossing flows at crossroads are present. This situation brings about unhelpful circumstances that can be avoided by implementing better strategies (a pessimistic scenario).

- Nearest exit (worst case): People leave at nearest exit. This strategy gives priority to the minimization of car kilometers. There will be no crossing flows at intersections so that the chance of queues and accidents at intersections will be reduced. However, the capacity of the network will not be used optimally (a pessimistic scenario).
- Traffic management (best case): Exits are used proportionally to their capacity, crossing traffic flows at intersections are avoided and car-kilometers are minimized (giving proportional use of exits). In this way directed, convergent, non-crossing traffic flows to the exit points are realized (an optimistic scenario).
- Detailed strategy in which certain zones are connected to specific exit points.

The entire road network is assumed to be available for evacuation and all people are assumed to be at home before the start of evacuation. No roads are assumed blocked due to construction or maintenance, no traffic is coming into the threatened area and no obstructions due to accidents during the evacuation are considered.

***Non-compliance and departure curve (citizen response)***

The response of each citizen depends on several factors, such as experience, trust in the government, the safety of family, friends, and ownership of pets (Perry, R.W., Mushkatel, P., 1984; van Duin, M.J. et al., 1995; Kok, M. et al., 2007). At the start of the evacuation, people are assumed to be in their homes, and roads are assumed to be empty. Before the decision to start an evacuation, other measures, decisions and crisis communications have been executed based on forecasts in accordance with national and regional emergency planning. People who evacuate spontaneously are assumed to be compensated by people who enter the area to support family and friends. Each scenario uses a departure curve that defines the moment when people leave their homes and take part in the traffic (Doef M. van der, Cappendijk P., 2006; Friso, K. et al., 2008). After 5 hours, 20% of the people leave their home for preventive evacuation; after 7 hours, 50%; 9 hours, 80%; and after 15 hours, 99% of the group that evacuates preventive has left their homes. These departure curves are based on experience in the United States and are appropriate for the Netherlands (Friso, K. et al., 2008). These curves take into account the time needed to respond and the influence of changing information in the response of the public.

Overall a non-compliance rate of 20% is taken into account. This 20% estimate is based on an enquiry by 'TNS NIPO' (NIPO, 2006) in the Netherlands as well as what has been learned from the experience during hurricanes induced evacuation in New Orleans. For river areas, in which more signals are available of high water levels and upstream flooding the non-compliance rate can reduce to 10%.

#### 2.3.2.3 *Types of calculation*

To get insight in the effectiveness of preventive evacuation, two different types of calculations are made in general:

- Static runs
- Dynamic runs

Static runs are made for sensitivity analyses and overall strategy development and risk analyses (using the model 'Evacuation Calculator', (Barendregt, A. et al., 2002)) This model takes into account the number of evacuees in the area, the distribution of departure of the evacuees in time, the road

capacities (as an average travel speed which takes congestion, accidents and behavior into account and a factor to take bad weather conditions into account) and the network, the exit capacity and the effects of traffic management. The parameters of the static model can be calibrated using the macroscopic model “Madame” (Meinen, M., 2006).

Dynamic runs are made to further optimize strategies and identify local bottle necks in emergency planning (macroscopic dynamic assignment model “Madame”). Dynamic runs are usually only done for the most interesting scenarios because these are more time consuming and complex: this model uses the (local) characteristics of the road network and takes into account the relationship between travel speed, intensity, road capacity and the number of vehicles during the evacuation.

#### 2.3.2.4 *Results*

The deterministic evacuation models describe the number of people as a function of time who can leave an area prior to flooding (Figure 14). The static model can also present the number of people which leave the area per exit. The dynamic runs also show the way the traffic spreads over the network over time (Figure 15).

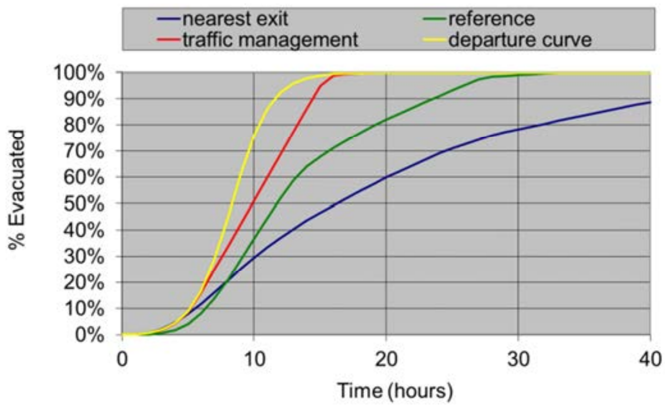



**Figure 14: Example of time needed for evacuation us static calculations using different management strategies**

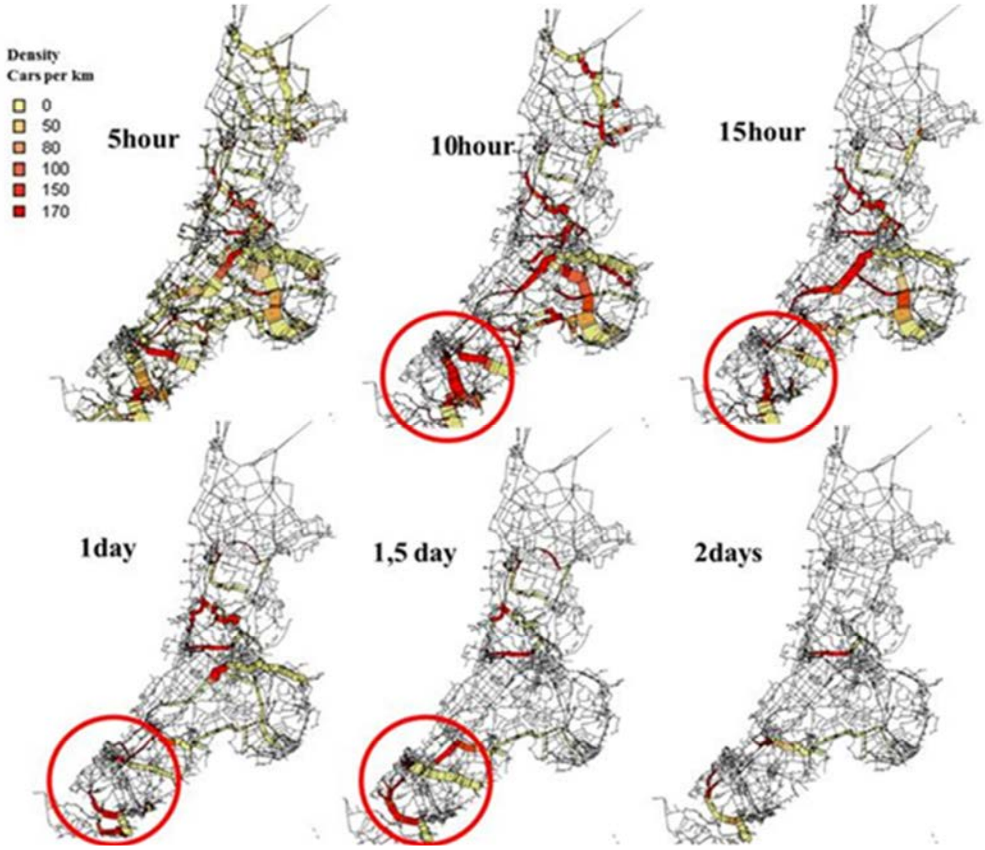



**Figure 15: Example of density on road network using dynamic calculations and bottlenecks for Coastal evacuation in the Netherlands**

### 2.3.3 EvacuAid, a probabilistic evacuation approach[2]

A scenario for evacuation describes the logistic progress and the number of people that reaches the intended destination over time based on a set of chosen boundary conditions and a pre-defined road networks. However the reality does often not meet the pre-defined scenario (Stijnen, J.W., 2007).

Evacuation models and models for loss of life can be used to describe the benefits of evacuation scenarios. These models take into account the local characteristics of the system that are affected by the event. In reality, each condition is uncertain. Knowledge about the impact of these uncertainties and their probability can be used to get insight into the relevance to influence these conditions by measures. These can be used to develop and compare different strategies for evacuation during emergency planning or during decision making in case of a threat.

#### *2.3.3.1 Scope of EvacuAid*

EvacuAid is developed to compare different strategies for evacuation during the transition phase (phase 2). EvacuAid supports decision-making about possible strategies as vertical, preventive evacuation or no evacuation and shows the effectiveness of implementing these measures.

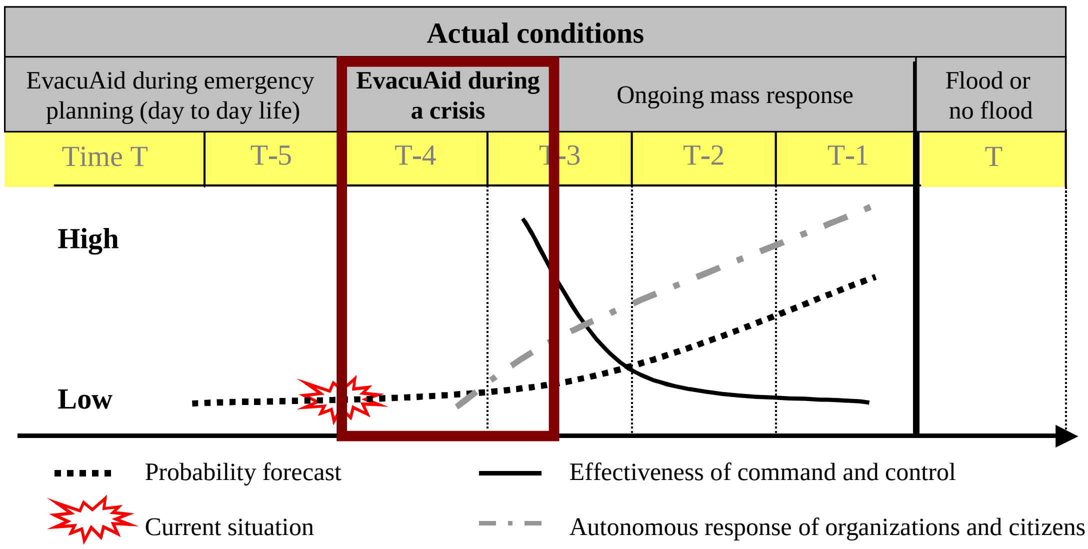



**Figure 16: Focus area of EvacuAid during the transition phase in emergency planning and the decision-making process during a crisis. (Rectangle indicates transition phase from normal to evacuation phase) (Kolen and Helsloot, 2012).**

The method can be applied for emergency planning because the possible situations based on uncertainties are taken into account. In case of a crisis the method can also be applied to support decision makers with strategy choices and the moment when to call for evacuation. Calculation time on a personal computer is less than a minute. After recognition of a threat, emergency planners can estimate the actual conditions of the four elements and mortality rates and estimate the impact of the measures.

[2] This chapter is based on: Kolen, B., Kok, M., Helsloot, I. and Maaskant, B. (2012), EvacuAid: A Probabilistic Model to Determine the Expected Loss of Life for Different Mass Evacuation Strategies During Flood Threats. Risk Analysis. doi: 10.1111/j.1539-6924.2012.01932.x

The method focuses on the selection process for an evacuation strategy before the actual start of an evacuation. Until that moment, measures can still be implemented adequately (e.g., traffic management), and the chosen strategy can be communicated to the public and first responders before they begin with their evacuations. The method cannot be applied in this form for an on-going evacuation (during phase 3). One can also question if such a model is relevant because the effectiveness of decision making and coordination will be limited in this situation. In the case of an on-going evacuation, it will be difficult to switch to another evacuation strategy. The combination of decision making, large-scale operational measures, re-allocation of means and rescue workers and citizen response without creating a grid lock may be impossible. Available information and the effectiveness of coordination are limited during these circumstances with regards to a reduction in loss of life.

#### *2.3.3.2 General description of methodology*

The method of EvacuAid uses different pre-defined scenarios for evacuation. The preventive evacuation scenarios can be developed by using the “High water Information System - Evacuation Calculator (HIS-EC) but also as LIFESIM or HEC-FIA. For vertical evacuation or shelter in place travel time is assumed to be zero.

For each preventive evacuation scenario the model run is based on a set of assumptions, such as the population that evacuates, the capacity of the infrastructure and the decisions of the authorities, first responders and the public. The probability of each scenario is related to the threat, use of infrastructure and when and how measures are taken by authorities and citizens (see Figure 17). Validation of evacuation models is, in most cases, not possible because data for mass evacuations are limited. Because of the lack of data, expert judgment has to be used to identify optimistic, realistic or pessimistic scenarios and their probabilities.

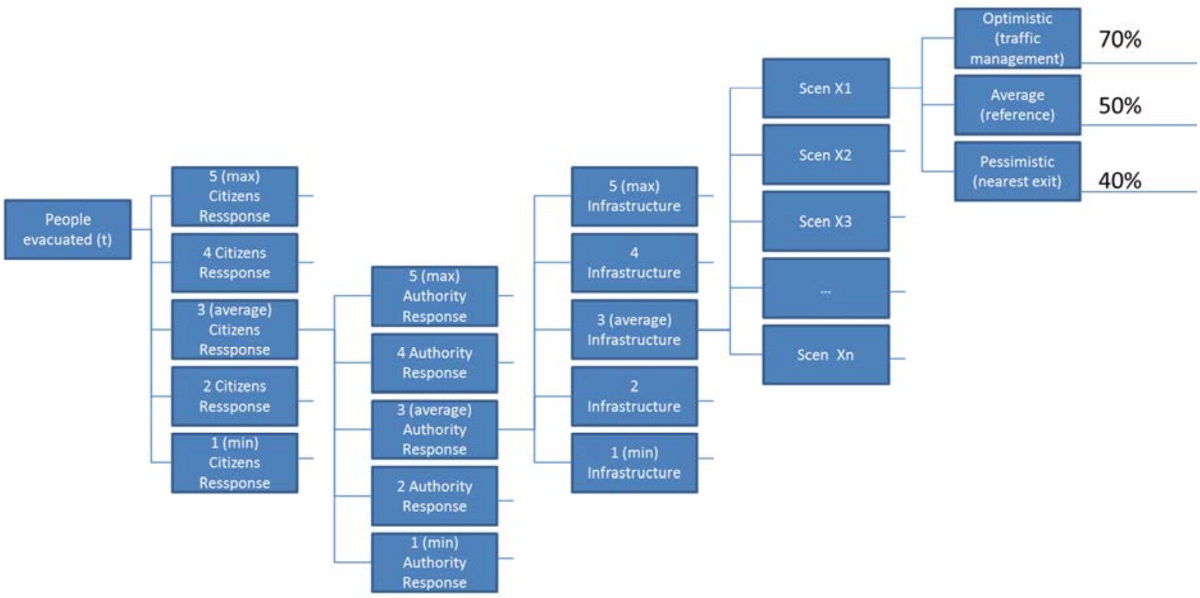



**Figure 17: Scenario in an event tree showing the number of people that can evacuate preventive**

EvacuAid assumes that of the people that not evacuate preventative, 50% will move to a public shelter; 40% will shelter in place and take precautions; and 10% will shelter in place without these measures. Those who are not evacuated preventive in time are assumed to be ‘hit while evacuating’.

### *2.3.3.3 Results of EvacuAid*

The interface of EvacuAid is shown in Figure 18. The timeline shows the time needed for decision making and implementation of measures and the time for evacuation itself. The left graph shows the number of people who reach the destination as a function of time. The right graph show loss of life taking into account the mortality rates as shown in the interface. The mortality rates can be changed by the user and have to be calibrated for the local situation. In this project we added an additional functionality to the EvacuAid model. We integrated the New Orleans mortality functions with EvacuAid, see section 3.5.2.2.

The user of the model EvacuAid can add the actual conditions for the elements of evacuations by the dashboard (Figure 18). In case of an event the actual conditions can be implemented, in case of emergency planning or other preparation activities the dashboard can be used to take different situations into account.

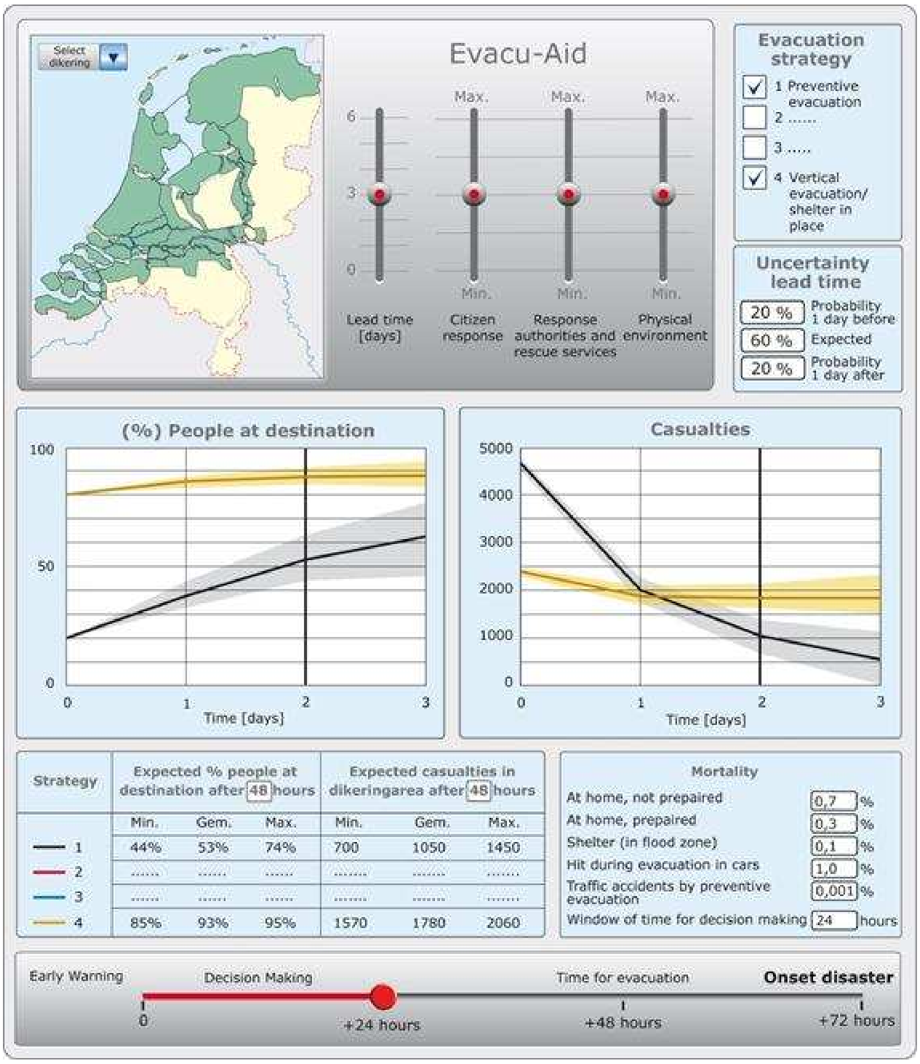



Figure 18: EvacuAid interface (Kolen et al, 2012).

Different strategies for evacuation can be compared to select the preferred strategy given the actual circumstances. The moment when a preventive evacuation (out of the threatened area) results in the same loss of life as a vertical evacuation (within the area) is called the “Evacuation Dilemma Point”. The moment when this Evacuation Dilemma Point occurs depends strongly on the characteristics of

the local area (e.g., the number of people, available roads) and the performance of the citizen response, the authority response and the use of infrastructure.

The combination of the results of EvacuAid and the probability distribution of the available time for evacuation (based on forecasts and decision making) can be used to define the evacuation fraction. The evacuation fraction defines the expected number of people which can evacuate from an area prior to flooding.

Figure 19 shows the dilemma point for an area taken different assumptions for the ‘quality’ of the parameters on the dashboard into account. In the left graph the citizens response, use of infrastructure and response of authorities is most positive, the models shows an average situation in the middle graph and the right graph the most negative situation. When conditions are worse the preventive evacuation (blue line) becomes less attractive than vertical evacuation (the red line).

The green blocks show the probability for a certain window of available time for evacuation. This means that in most cases 2 days are available for evacuation. This two day period is equal to the dilemma point in an average situation. So in an average situation the preventive evacuation results in the same loss of life as the vertical evacuation strategy. When loss of life is the equal for both strategies other factors become important for decision makers. For example in case of a preventive evacuation the economy will be disrupted more than in case of vertical evacuation.

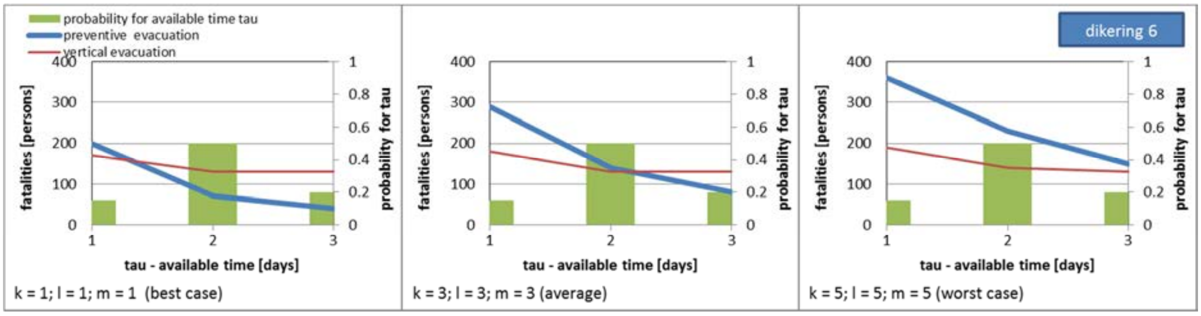



Figure 19: Example of dilemma point and relation with probability distribution of available time (Kolen et al, 2012).

### 2.3.4 Evacuation approach implemented in HEC FIA

#### *2.3.4.1 Population*

HEC-FIA uses a geospatially based methodology to describe the built inventory.  Structures are defined as points on a map for x and y location, and have their z value or elevation determined by a digital elevation map (DEM). Structures can be added into HEC-FIA through many different methodologies, by point shape file (for surveyed structures), parcel data (if geospatial data describing the location of the parcels), or from the HAZUS database. The structure inventory is described by a series of attributes, damage category allows the user to aggregate like structures together (residential, commercial, industrial), occupancy type allows the user to specify differences within a damage category (residential with or without basements, multiple stories, multiple family dwellings, masonry or wooden etc), foundation heights, values, and population. The most rapid way of generating a structure inventory is to use the HAZUS database. The HAZUS database is a product generated by FEMA that represents the entire United States at the state, county, tract and census block level.  The data represented consists of structures and characteristics about those structures, and population and characteristics of the population, the smallest geographic representation is the

census block. HEC-FIA accesses the data at the census block level, extracts relevant information and creates a uniform grid based on structure density and creates individual structures at the vertices of the grid within the census block. FIA then distributes the population within the structure inventory based on building type. The building type is correlated to a quantity of households. FIA then calculates the population for both day and night, and the proportion of the population that is over or under 65 for those two times of day. Once the total number of people is determined by census block it is divided by the total number of households, and then each structure receives the number of people based on how many households it contains. This process is intended to determine the population exposed during the day and the night since the population moves in and out or to different locations within the floodplain based on time of day. The HAZUS data is based on the US CENSUS and since that is only conducted once every ten years the population data can be inaccurate, to facilitate the process of updating that information HEC-FIA allows the user to define regions where population has fluctuated and by how much it has fluctuated to more accurately describe the exposed population.

#### 2.3.4.2 Departure (warning and mobilization)

To describe the human response to flood warning, HEC-FIA has used existing research that created a mathematical representation of response to warning issuance. The research was done by George Rogers and John Sorensen to analyze the response to warnings for chemical release, nuclear disaster, and other natural disasters. The general framework of the mathematical representation of this relationship is dependent upon what system is being used to relay the warning issuance (EAS, reverse 911, sirens, etc.) and what the population is doing at the time of the warning issuance. The formula represents the fraction of the population that is warned for any time step. In this framework warned means that the individual has heard and fully understood the warning that was issued. This distinction is important, because some warning methodologies are only an alert system, for instance sirens do a sufficient job to alert the public something is going on, but not much information describes the direct hazard that the warning is being used for. In those instances there must be a representation of how much time it takes for an individual to fully understand the threat and necessary reaction. A general framework is shown in figure 2. The mathematical formula is split into two portions, the first half of the equation describes the initial warning itself, and the second half describes the secondary warning process. When an individual is warned, they are able to warn other individuals at risk within the floodplain through any available methodology with the secondary warning process.

Once the warning has taken place, the population enters the mobilization portion of this process. Mobilization describes the time it takes for a person to react appropriately given a warning. After fully understanding the threat and required actions, individuals have to determine if the threat directly applies to them, and if it does, typically the individual will then take some time to gather any necessary items to take with them when they evacuate. The alternative name for this process would be the mulling process. This process is defined by a curve within HEC-FIA that shows the number of people who begin evacuation over time, generally the mobilization curve max will be no greater than 98% since there is a portion of the population who if given warning will refuse to take appropriate action. The warning curve and the mobilization curve are then combined through a process that takes the marginal amount of people who were warned in the previous time step into the mobilization process, and so on. The combined mobilization curve ultimately describes the rate at which the population enters the evacuation network. This process is modeled individually at each

structure, but is represented as a percentage of the total population for that given structure, therefore, the methodology is trying to suggest that the population is homogeneous, and reacts generally the same across the floodplain to the given warning.

#### *2.3.4.3 Evacuation*

Upon mobilization the individual enters the evacuation process. HEC-FIA simplifies this process and uses a straight line from the structure to the nearest safe location to represent the evacuation path. This path is followed at a user defined nominal velocity, so HEC-FIA calculates the distance of the line and multiplies the evacuation velocity times the distance of the line to come up with the time it takes for the individual to get to safety(safety is defined by less than 2 ft of water). Alternatively the user can define the time it takes for any structure to evacuate to safety.

### 2.3.5 Evacuation methods comparison

***General comparison***

A comprehensive comparison of the various modeling approaches is included in Table 2 below.

| | **HIS-EC (NL)** | **EvacuAid (NL)** | **HEC-FIA (USACE)** | **LIFESIM (USACE)** |
|---|---|---|---|---|
| **Model type (for evacuation)** | Deterministic for scenario analysis. A static black box model | Probabilistic model using a database of scenarios | Deterministic for scenario analysis<br><br>A static black box model | Deterministic agent based model for scenario analysis |
| **Population** | People are related to zones | People are related to zones | People are related to structures | People are defined as unique avatars |
| **Evacuation application / timing of evac** | Evacuation before breaching | Prior to flooding during onset of evacuation | Evacuation before and after breaching / flooding | Evacuation before and after breaching / flooding |
| **Safe locations** | Exit point in road network of local safe haven | Different locations with a unique mortality rate | Nearest location with 2 ft of water | |
| **Transport and network** | Car, road network has to be defined. The model used an average travel speed and outlflow reduction factor. | As used in model to develop scenarios | Walking | Car, road network has to be defined. Actual capcities are taking into account of road network |
| **Route choice** | 4 different possible algorithms (pessimistic to optimistic to user defined) | As used in model to develop scenarios | Shortest distance to 2ft water depth in pre-defined flood | Shortest distance, people are redirected when confronted with a |

| | | | | |
|---|---|---|---|---|
| | | | scenario | flood |
| **Relation with a flood** | No relation | Using Jonkmans functions or a user defined mortality rate | Flood scenario has to be defined in advance | Flood scenario can be added and influences evacuation |
| **Departure curve** | Pre-defined combining warning and mobilisation | As used in scenarios | Combination of warning and mobilization, depends on warning | Combination of warning and mobilization, depends on warning |
| **Calculation time (for Natomas)** | Minutes | Seconds | | |

Table 2: Evacuation methods comparison.

### *Comparison of available time*

Scenarios for evacuation can be developed with HEC-FIA, LIFESIM and HIS-EC. In theory these scenarios can describe the evacuation prior to a flood, HEC-FIA and LIFESIM also consider interaction with a flood. HEC-FIA and LIFESIM can be used to estimate the number of people which can evacuate during a flood. However the used algorithm in these models assumes that during the evacuation information is known about water depths and nearest exists. These assumptions require information (and coordination by emergency services) about the ongoing evacuation and flood scenario. In reality this information is very uncertain, for example different flood scenarios can occur. It can also be questioned if the information is available, therefore it has to be gathered, analyzed and spread over all people who are evacuating.

### *Comparison of departure curves*

Each scenario uses a departure curve that defines the moment when people leave their homes and take part in the traffic (Doef M. van der, Cappendijk P. 2006; Friso, K. et al. 2008). HEC FIA and LIFESIM assume more detail in the departure of people compared to HIS-EC. The departure of people is based on the process of warning and the process of mobilization. The need for more or less detail to describe departure depends on the characteristics of an area. Knowledge of the time needed for the three phases of evacuation (departure, travel, exit) can be used to estimate the required level of detail. When the travel time is most significant for the total time for evacuation the importance of more detail in the departure curve is limited. When the departure time is most significant (for small areas for example) the process of departure is more significant for the total evacuation time. The analysis of Natomas shows that travel time is more significant. Also the used departure curves by HIS-EC and the departure curve by HEC FIA and LIFESIM (combination of the warning and mobilization) are almost equal (Figure 20).

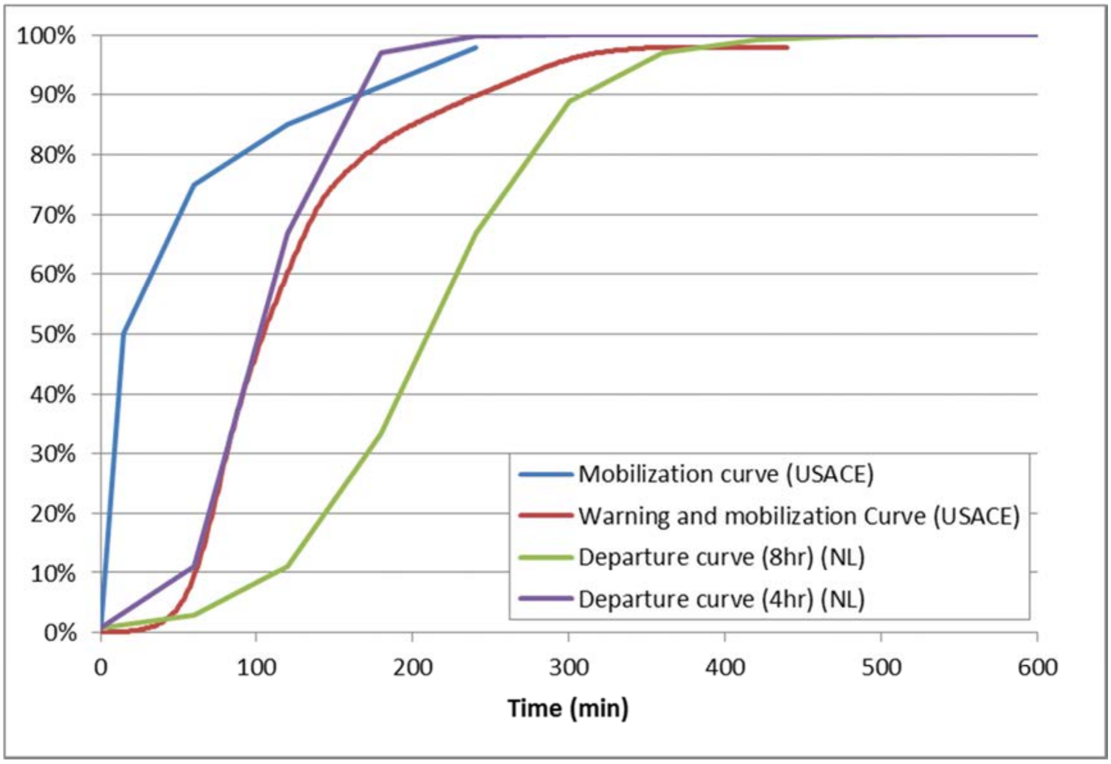



Figure 20: Departure curves in the models as used for Natomas and in the Netherlands

### *Comparison on types of evacuation scenarios*

The realism of a specific scenario can be questioned because models are not validated for evacuation. The realism depends on the boundary conditions of the models and the used algorithms. For example HEC-FIA assumed people to walk to a nearby safe place. HIS-EC can take different forms of origin and destinations into account. The model EvacuAid can be used to deal with knowledge of the realism of different scenarios and developed expected values the number of people which can evacuate, estimate loss of life for different strategies for evacuation and a bandwidth.

# 3 Natomas Basin case study

## 3.1 General area description

The Natomas Basin is a low-lying area of approximately 222 $km^2$ that is situated in Sacramento-San Joaquin Delta in California. This area is protected against flooding by 69 km of levees, which protect the area against flooding at the western boundary from the hazard of Sacramento River and at the southern boundary from the American River. Three canals bound the area at the North, the Natomas Cross Canal (NCC), and the West, the Natomas East Main Drainage Canal (NEMDC), Pleasant Grove Creek Canal (PGCC). The levee system of Natomas Basin is designed to meet the 200-year flood protection level.

The area is relatively flat with an elevation ranging approximately between 3 to 12 meter above mean sea level, where it should be noticed that the surface elevation of the adjacent land to the levee is lower than the water surface level of the Sacramento and American River [NA, 1995]. The 100-year floodplain of the rivers and local drainage systems covers the entire area of Natomas Basin [NA, 1995]. See Figure 21 for a geographical overview of Natomas Basin and the elevations in meters.

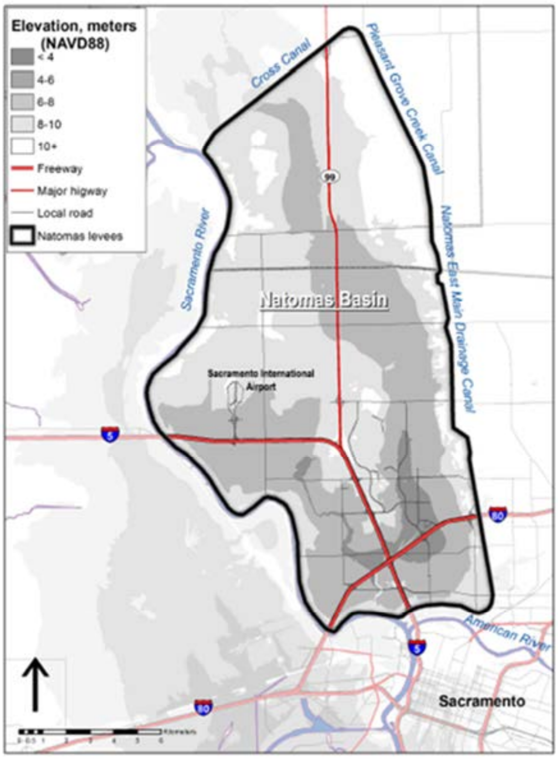



Figure 21: Geographical overview Natomas Basin with the elevation heights in meter above mean sea level ([Jonkman et al., 2012])

Two interstate Freeways (5 and 80) are crossing Natomas Basin and connect the area with the other parts of Sacramento. The third mayor road is the 99 highway up to the North.

The Sacramento International Airport is located in the midwestern area close to the Sacramento River. This airport is an important hub for both national and international transfer flights.

The population density varies over the Natomas Basin. The northern part of this area (Sutter Counties) is not densely populated at all, but the southern part (Northern Sacramento) is very densely populated. In the year 2010, over 100,000 residents were living in this area. The population in this area is rapidly urbanizing, since in 2000 only approximately 40,000 people were living in Natomas Basin.

This chapter describes the results of a loss of life analysis for the Natomas Basin.

## 3.2 Data and assumptions

This section outlines the used data and made assumptions in the loss of life analysis, with respect to the flood scenarios (section 3.2.1), flood maps (section 3.2.2) and population data (section 3.2.3).

### 3.2.1 Flood scenarios

In the Sacramento-San Joaquin Delta in California three types of levee failure scenarios are distinguished:

1. High-water flood overtopping without breaching
2. High-water flood failure: overtopping with resulting breaching
3. Sunny day failure: breaching  without overtopping of the levee

In the high-water flood scenario, high river discharges flows through the Sacramento River and the American River with the possible undesirable result of only overtopping (scenario 1) or even a breach of the levee system. High-waters occur in the early spring, caused by heavy winters and spring rains lasting up at least three weeks [Porter et al., 2011].

The sunny-day failure scenario (scenario 3) occurs outside the flood flow period, due to levee instability and/or seepage. A geotechnical sunny-day failure can occur at any water level at the Sacramento River and the American River.

Flooding of the Natomas Basin may result due to different possible failure scenarios of the levee system. The fault tree (see Figure 22) gives an overview of all these possible scenarios. USACE provided data for three breach locations for seven different flood scenarios, which are included in the fault tree. Besides, other failure scenarios at different location can be identified. These are marked as ‘other’ in the fault tree. The presented fault tree of failure of Natomas Basin only includes individual (singular) flood scenarios, where as a multiple breaching failure event is possible as well. These events are not considered in this case study.

The consequences of the each flood scenario are expressed as the loss of life in this case study. The expected number of fatalities depends on the effectiveness of the evacuation process. Each possible flood failure event in the fault tree can be extended with possible evacuation strategies. In the comparison of the loss of life models the assumption is made that no evacuation is performed (preventive evacuation is 0%). The resulting expected number of fatalities is a maximum scenario, based on the underlying flood scenarios.

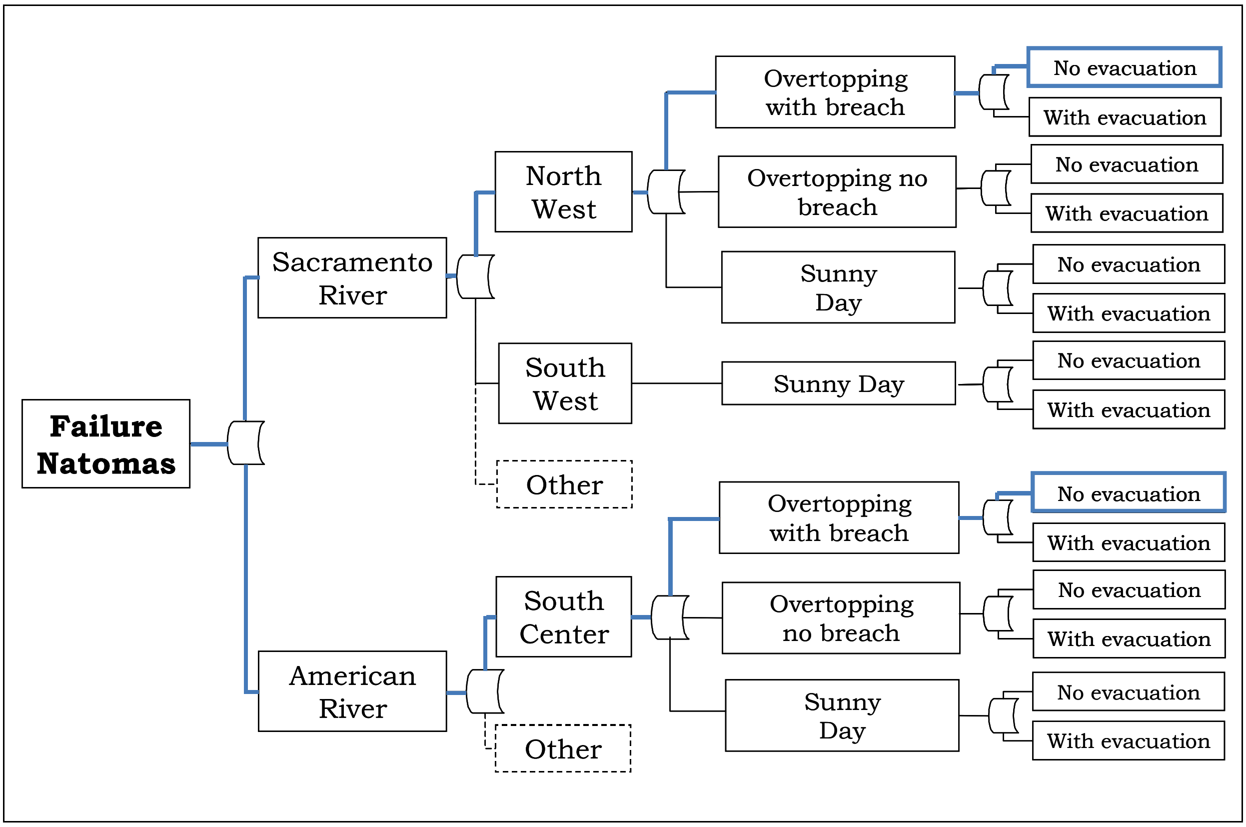



**Figure 22: Fault tree Flooding hazards Natomas Basin, solid blue lines are considered in the analysis.**

In this case study the loss of life is determined for two flood scenarios that describe high-water flood failure scenarios with overtopping and a resulting breach along:

1. Sacramento River – Northwestern breach (lateral structure 79.2)

2. American River – South center breach (lateral structures 1.738 and 2.101)

Figure 23 presents a geographic overview of both breach locations.

The first breach location is the most upstream situated breach along the Sacramento River. Breach location number 2 is the most southern breach and is situated nearby the populated areas.

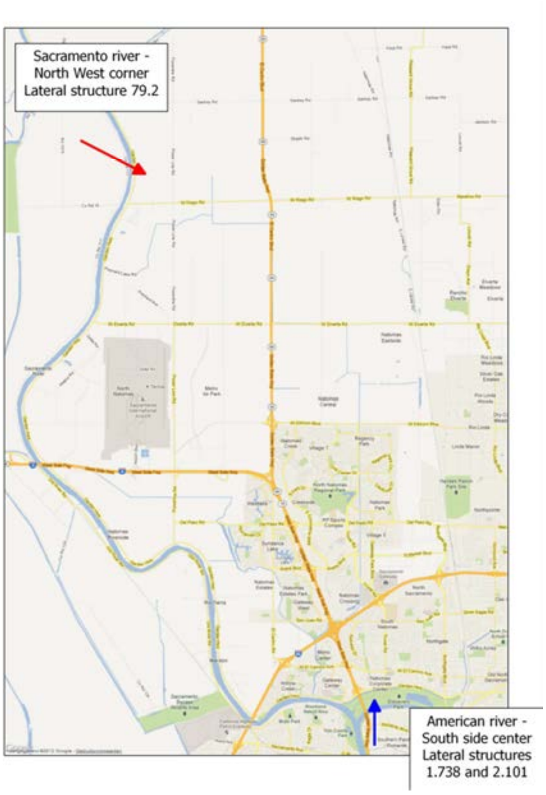



**Figure 23: Geographical overview breach locations along the Sacramento River and the American River**

### 3.2.2 Flood maps

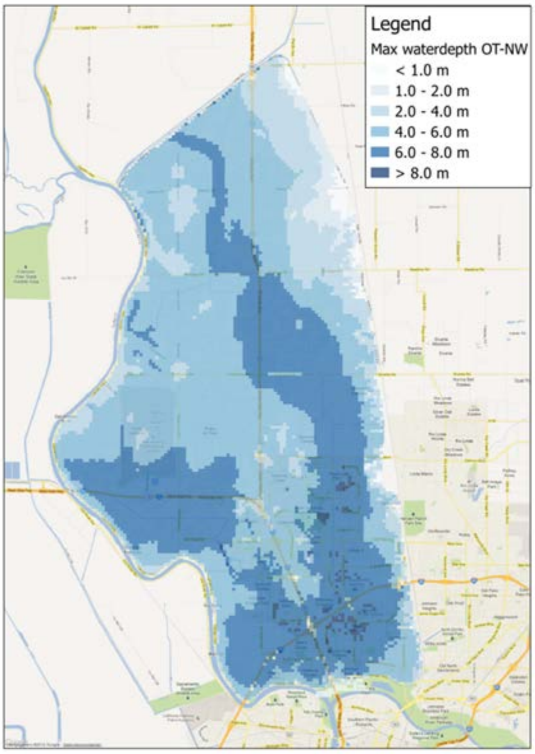
A 2-dimensional flood model can describe each possible flood scenario by its flood characteristics. The flood characteristics exist of spatial distribution of the water depth, flow velocity, rate of rise, time of arrival and time of departure. The flood characteristics can be presented by flood maps, which are the input files for the loss of life analysis. The following flood characteristics determine the mortality rate in the various models:

- max water depth [m]
- max velocity [m/s]
- rate of rise [m/hr]

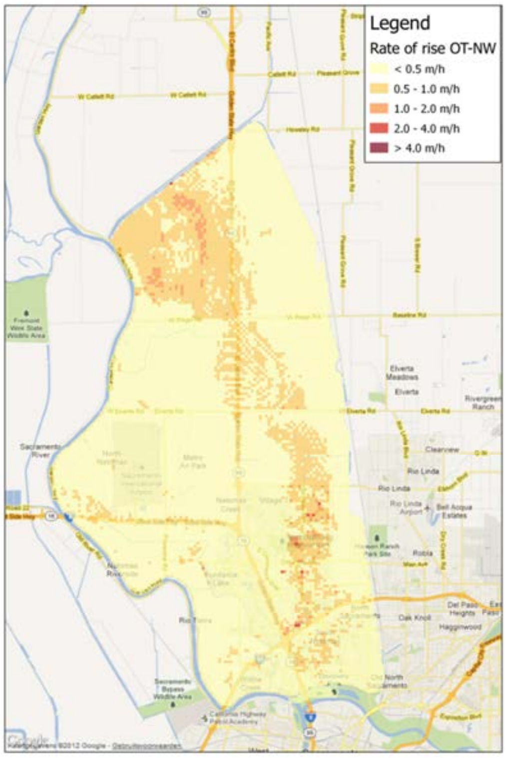
The extent of the flood depends on multiple input parameters, e.g. water level, breach development, duration of the flood event, elevation surface level (terrain model), roughness factor.

This section shows the flood maps of both flood scenarios (source: flood characteristics provided by USACE). This flood maps are input files for the loss of life analysis. The loss of life functions of Jonkman [Jonkman S.N. (2007)] are based on flood data in meters.[3] Therefore the provided flood data are converted from feet to meters.

[3] Formula used for conversion feet to meter: depth in meters = depth in feet * 0.3048




Max water depth [m] – Overtopping with breach North West Sacramento River (OTNW)

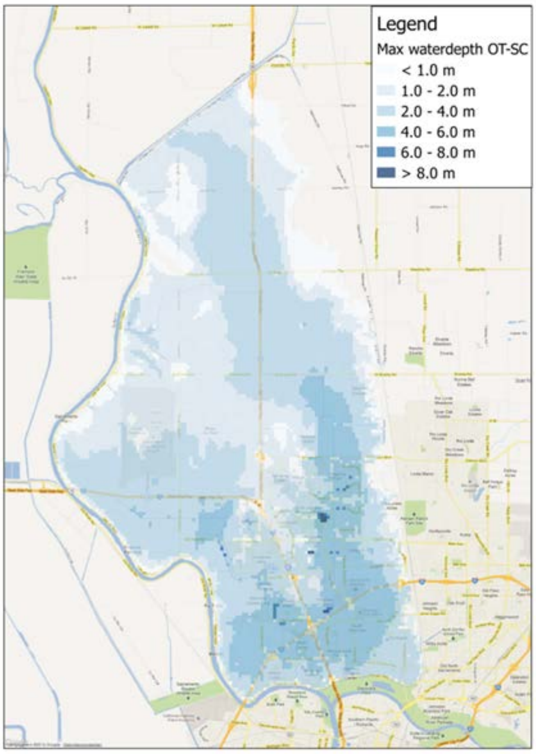



Max rate of rise [m/h] – Overtopping with breach North West Sacramento River (OTNW)

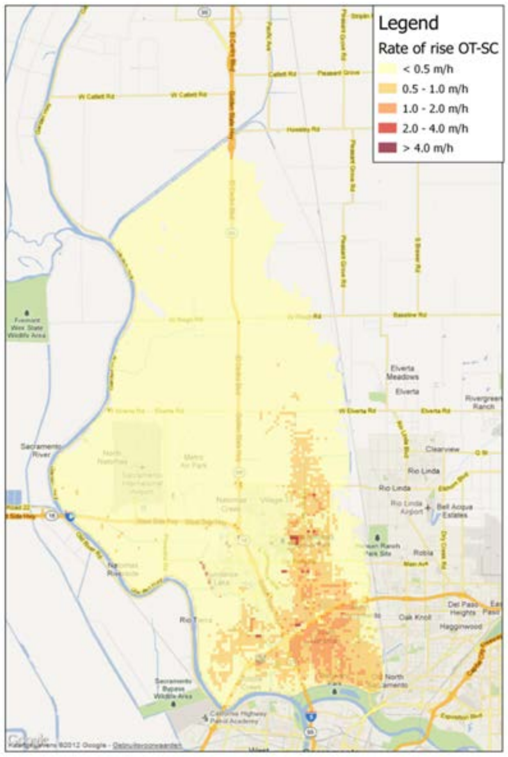
**Figure 24: Flood scenario North West Sacramento River.**

The flood characteristics for breach 1 are shown in Figure 24, with the maximum water depth shown at the left side and the rate of rise at the right side of the figure. The maximum water depth varies over the area.  The largest water depths occur in the southern part of Natomas Basin, with mainly water depths between 6 to 8 meters and a couple of spots a water depth over 8 meter. Part of the very high water depths occur a locations where a park is situated. These types of areas are low-lying and are not (dense at all) populated.

The rate of rise is max 1.0 m/hr for the largest part of Natomas Basin. The rate of rise amounts over 1.0 m/hr to 2.0 m/hr in the area close to the breach. In the densely populated area in the South there are only a couple of single spots where the rate of rise is larger than 1.0 m/hr.




Max water depth [m] – Overtopping with breach Center Side of American River (OTSC)




Max rate of rise [m/h] – Overtopping with breach Center Side of American River (OTSC)

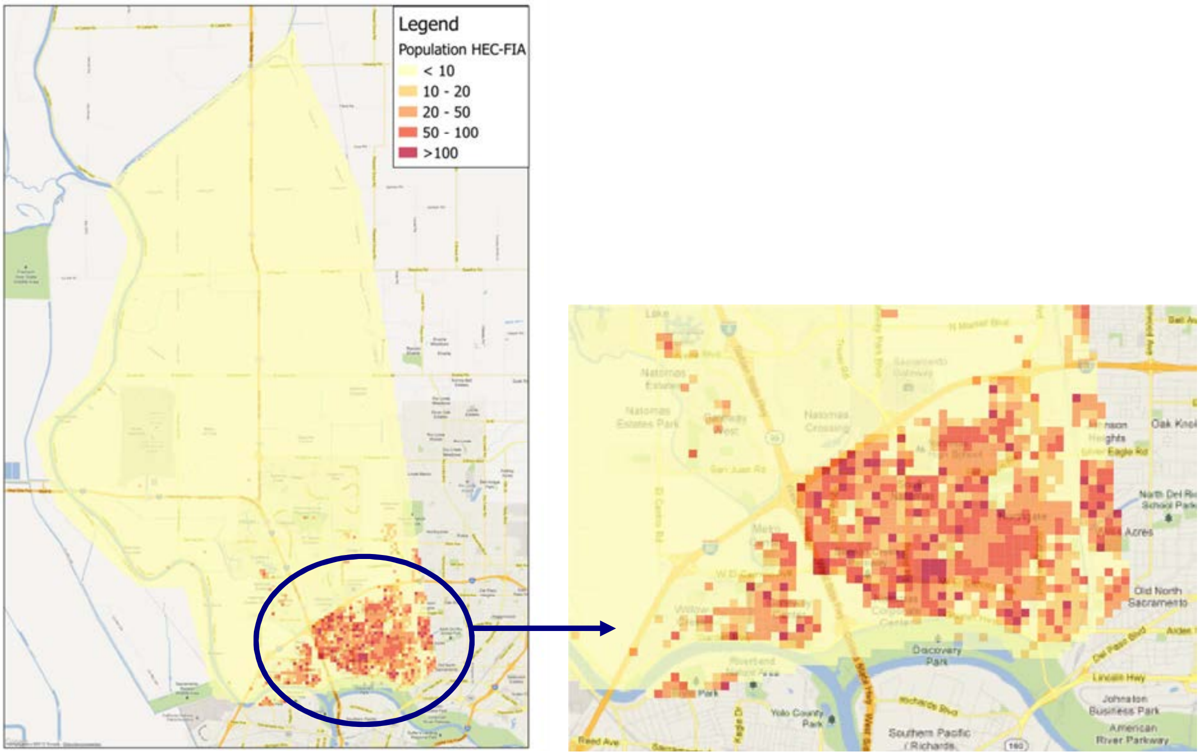
Figure 25: Flood scenario Center Side American River.

Figure 25 shows the flood characteristics for breach 2, with the max water depth shown at the left side and the rate of rise at the right side of the figure. It can be noticed that the water depths are lower in comparison with a breach at breach location 1 in the Northwest. For most of the area the maximum water depth is less than 4.0 meter. However, the larger water depths now occur in the southern part of Natomas Basin where most of the population is located. The larger rates of rise occur in the southern area of Natomas Basin as well. This contributes to higher mortality rates with the interpolated 1953 method (see next section).

### 3.2.3 Population data

The population data that is used for this loss of life analysis is provided by USACE. The population data represents the population of Natomas Basin at night for the year 2000 (see Figure 26). The registered population per block group level is distributed over the number of houses in the block group. This population data is implemented in HEC-FIA by USACE.

The number of people that lives in the flood exposed area amounts 40.000. The population data for the year 2010 included over 100.000 residents in Natomas Basin. Since the 2010 population data is not area-wide available on the more detailed block group level (only census blocks), this data could not be used in this loss of life analysis. It should be noticed that the expected number of fatalities will be on average three times as large for the 2010 population data, as for the 2000 population data.




Population data based on HEC-FIA: right plot shows a detailed overview of the highly dense populated area of Sacramento

Figure 26: population data Natomas basin (year 2000).

### 3.2.4 Other assumptions

The following other assumptions are made in the loss of life analysis:

- No preventive evacuation in the loss of life method (interpolated 1953 method and New Orleans method);

## 3.3 Loss of life

In this section an overview is given of the results of the loss of life analysis with the following four methods: the Interpolated 1953 method (section 3.3.1), the New Orleans method (section3.3.2), HEC-FIA (section3.3.3) and Lifesim (section3.3.4). The conclusion of this comparison effort is outlined in section 3.3.5.

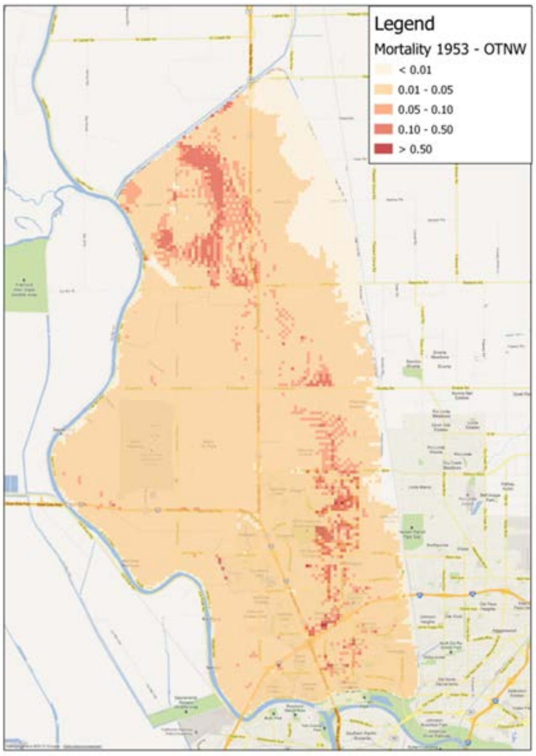
### 3.3.1 Interpolated 1953 method

The interpolated 1953 method is used to determine the loss of life for the Natomas case study. For theoretical information about this method reference is made to section 2.2.1.

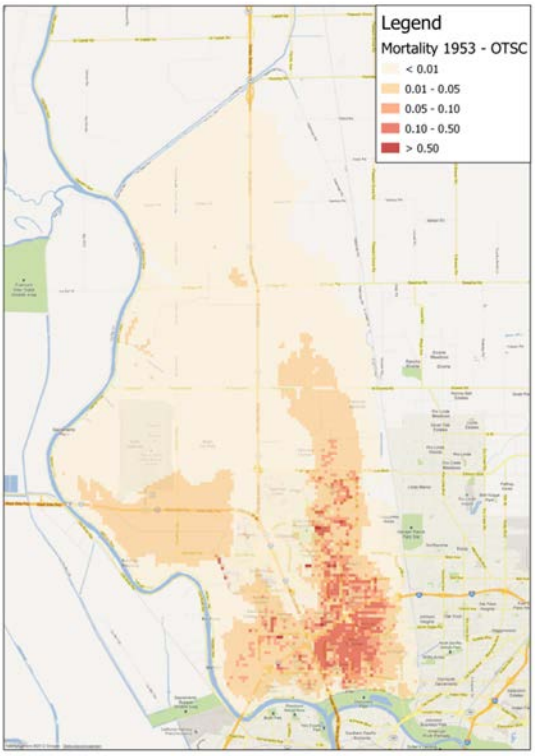
The rate of rise is the most influential parameter in the mortality functions for the interpolated 1953 method. In a relative sense, the outcomes are more sensitive for the value of the rise rate than for the water depth.

Since a breach along the American River has large rise rates and relatively moderate water depths to result in the highly dense populated, the mortality rate is quite large in this area (between 10 and 50 per cent).

The breach along the Sacramento River at the Northwestern stretch results in large rise rates at the Northern part of Natomas Basin, which is not so dense populated. Due to this breach large water depths occur in almost the whole area, but as just has been noted large water depths determine the mortality rate to a lesser extent in the interpolated 1953 method.




Mortality - Overtopping with breach
North West Sacramento River (OTNW)




Mortality – Overtopping with breach
Center Side of American River (OTSC)

**Figure 27: Mortality for the interpolated 1953 functions for the two scenarios.**

Table 3 shows the results of the loss of life analysis based on the interpolated 1953 method. The number of fatalities is expected to be twice as large due to a breach at the American River then due to a breach at the Northwestern section of the Sacramento River. This can be clarified by the difference in rise rate in the residential area in the southeast area of the basin.

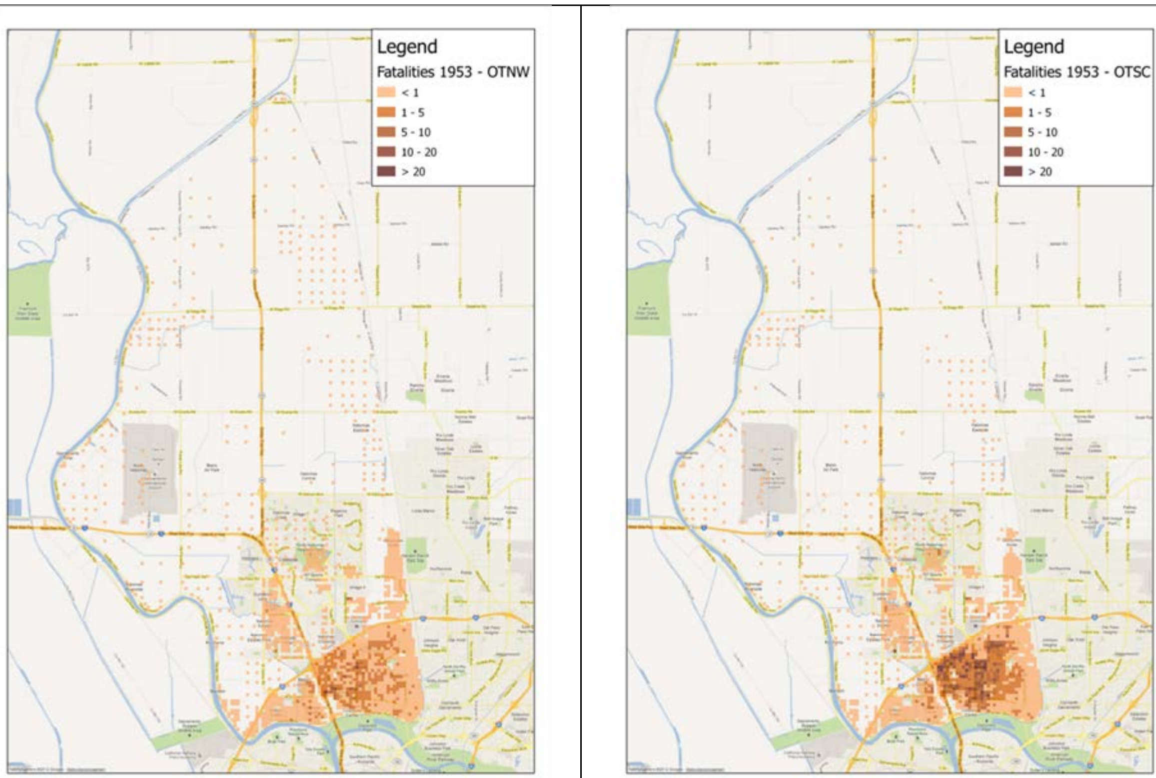
| **Interpolated 1953 method** | **Flood Scenario – Overtopping with breach** | |
|---|---|---|
| | Sacramento River – North West | American River – Center Side |
| Fatalities – no evacuation[4] | 910 | 1810 |

**Table 3: Overview number of fatalities in case of a overtopping with breach for the two breach locations (year 2000 population).**

From the 2010 population perspective, it is expected that the number of fatalities for both flood scenarios will be about three times larger.

[4] Based on the population data of 2000 with totally 40,000 residents.

Figure 25 shows the spatial distribution of the estimated loss of life for both breaching scenarios. It is noted that regular patterns of dots in the north of the basin is due to the way the population is assigned in the population dataset generated by USACE.




Fatalities - Overtopping with breach North West Sacramento River (OTNW)

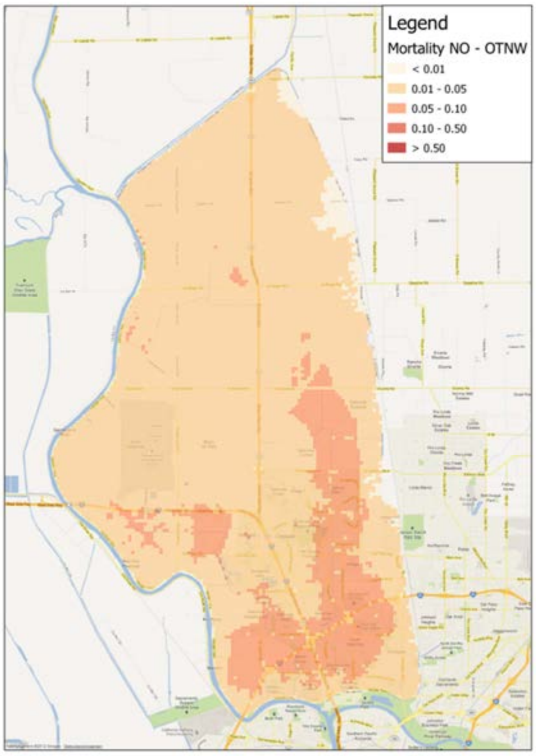
Fatalities – Overtopping with breach Center Side of American River (OTSC)

Figure 28: Fatalities for the interpolated 1953 functions for the two scenarios.

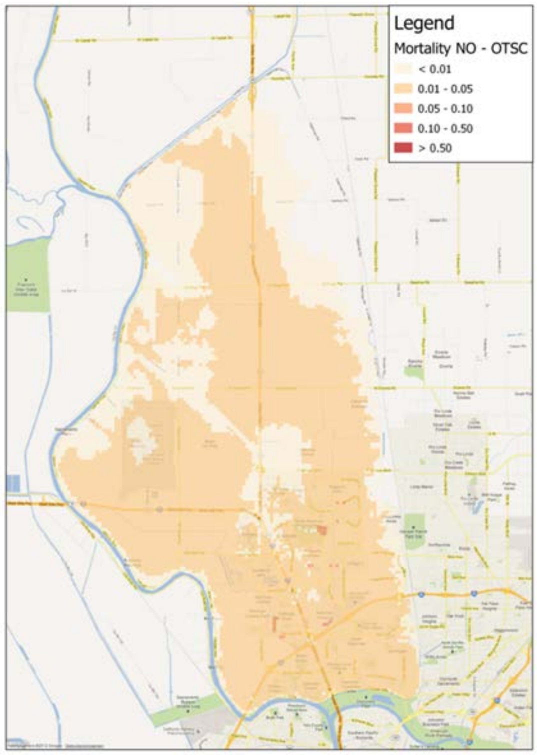
### 3.3.2 New Orleans method

The second method that is used to determine the loss of life for the Natomas case study is the New Orleans method. For theoretical information about this method you are referred to paragraph 2.2.2.

The mortality functions of the New Orleans method do not include the effect of the rise rate on the mortality. Next to that the mortality is much lower in the breach zone (about 5% to 10%) in comparison with the Interpolated 1953 method where it is 100%. In the following two figures the mortality rates are shown for the two scenarios.




Mortality - Overtopping with breach
North West Sacramento River (OTNW)




Mortality – Overtopping with breach
Center Side of American River (OTSC)

Figure 29: Mortality for the New Orleans functions for the two scenarios.

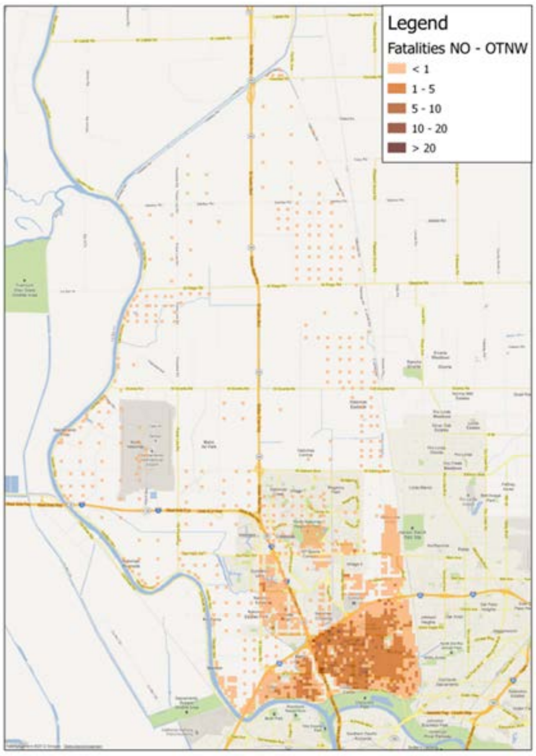
The number of expected fatalities in case of flooding of the Natomas Basin will be larger in case of a breach along the Sacramento River at the Northwestern stretch, since in that case the maximum water depth has the largest extent in the highly dense populated area. The water depths are relatively moderate in this area in case of a breach along the American River, but still results in over 1000 expected fatalities. Table 4 shows the results of the loss of life analysis based on the New Orleans method. The number of fatalities is expected to be two-and-a-half times as large due to a breach at the Northwestern section of the Sacramento River compared to a breach along the American River. Remark, that this is contrary to the conclusion of the loss of life analysis based on the Interpolated 1953 method.

| **New Orleans method** | **Flood Scenario – Overtopping with breach** | |
|---|---|---|
| | Sacramento River – North West | American River – Center Side |
| Fatalities – no evacuation[5] | 2810 | 1100 |

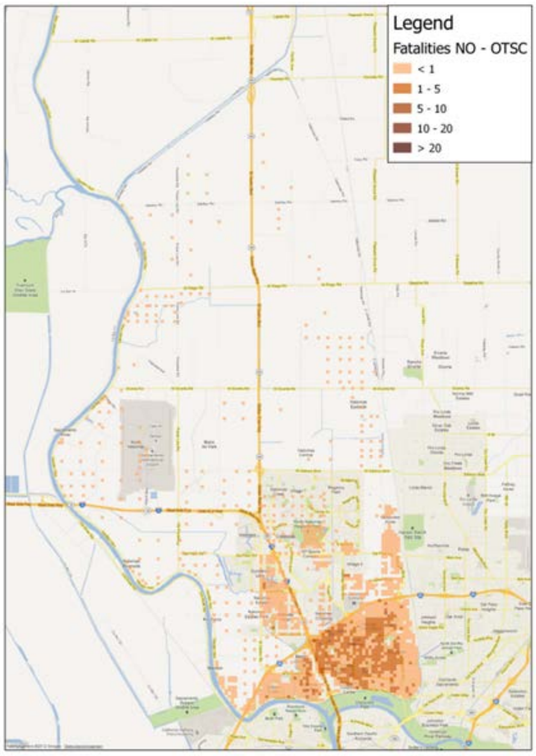
Table 4: Loss of life estimated with the Katrina mortality functions (year 2000 population).

In the following two figures the spatial distribution of the fatalities is given for the two scenarios.

[5] Based on the population data of 2000 with totally 40.000 residents.




Fatalities - Overtopping with breach
North West Sacramento River (OTNW)

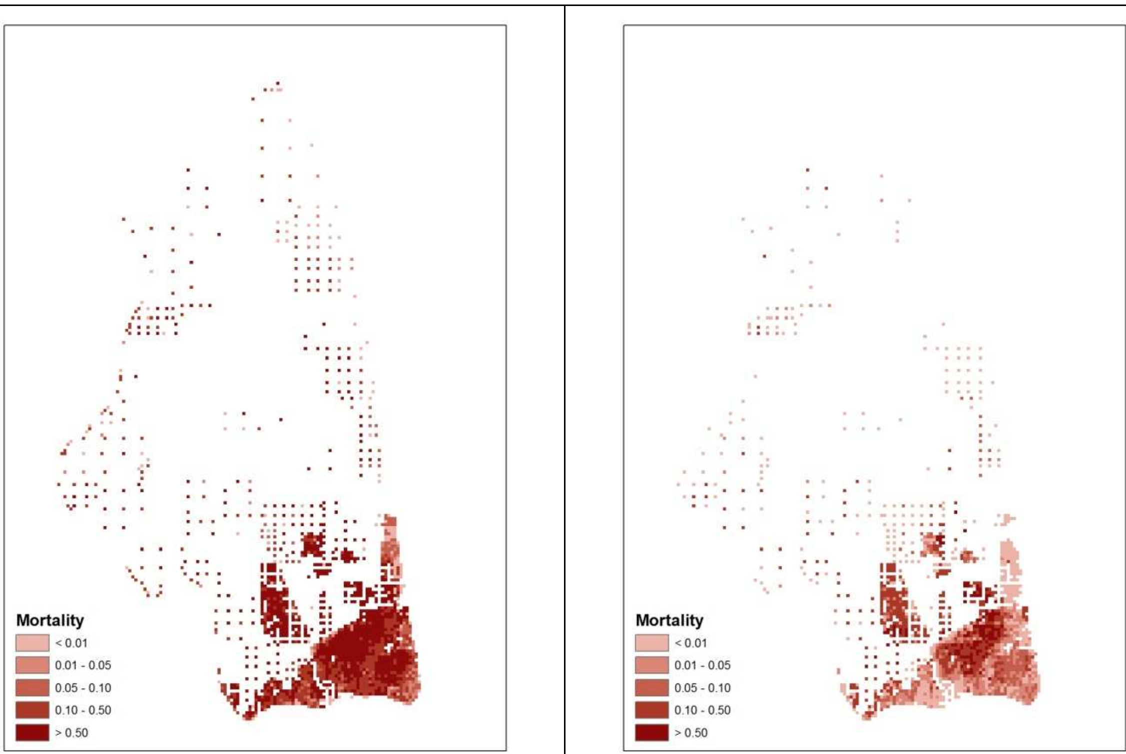



Fatalities - Overtopping with breach
Center Side of American River (OTSC)

**Figure 30: Fatalities for the New Orleans functions for the two scenarios.**

### 3.3.3 HEC-FIA

Loss of life for the two scenarios has been computed with HEC FIA. Figure 29 shows the mortality for both scenarios. Since mortality is related to structures, only mortality can be displayed for locations where structures are present. Within HEC FIA and the assumed settings for this comparison, no evacuation is assumed. Mortality is then related to flood depth (see figures 10 and 11). Mortality is particularly high with values of 90% when the flood depth exceeds 5m. For the Northwestern breach this is the case for most places in the southern part of the basin (See fig. 29, left). Mortality values are a somewhat lower for the breach in the south since this is associated with lower flood depths (see fig. 29, right).




| Mortality - Overtopping with breach North West Sacramento River (OTNW) | Mortality – Overtopping with breach Center Side of American River (OTSC) |
|---|---|

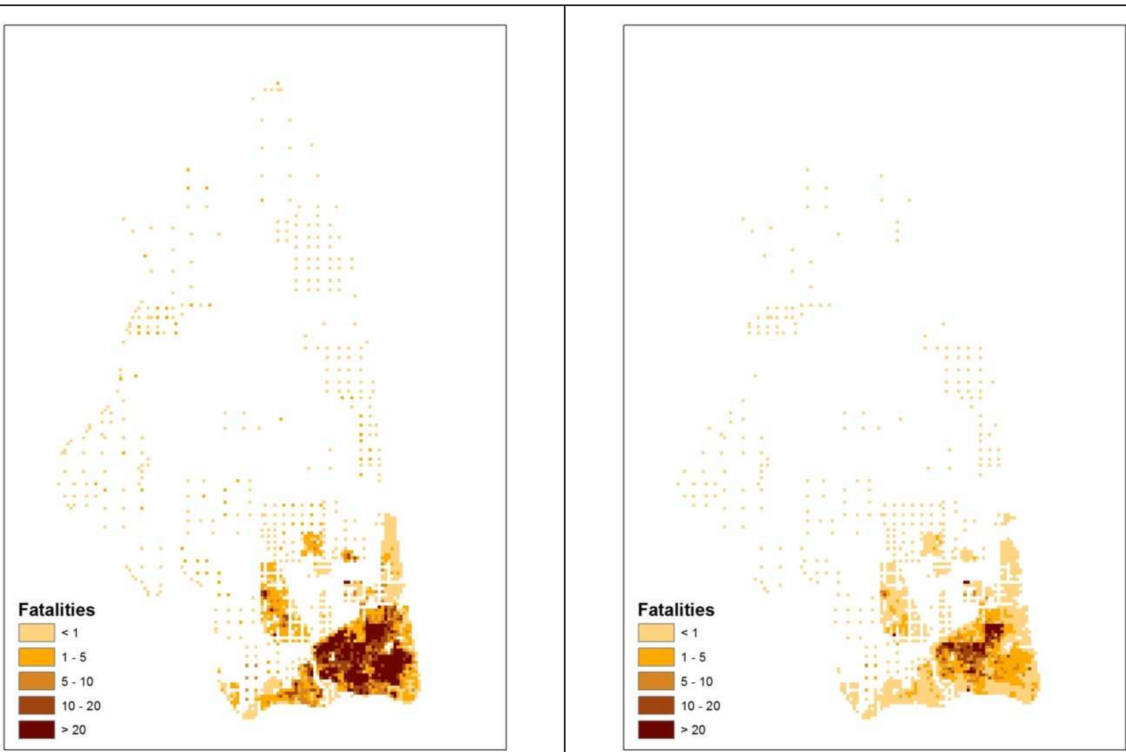
Figure 31: Mortality for the HEC-FIA method for the two scenarios.

Table 4 displays the total life loss estimates with HEC FIA for both scenarios and figure 30 shows the spatial distribution. Life loss is particularly high with more than 18,000 fatalities for the breach in the northwest. In this case very high flood depths occur in the southern part of the basin (more than 4 to 5m) and mortality rates and life loss will become high. Life loss is still high for the American river breach with more than 4,000 fatalities.

| HEC-FIA method | Flood Scenario – Overtopping with breach | |
|---|---|---|
| | Sacramento River – North West | American River – Center Side |
| Fatalities – no evacuation[6] | 18,412 | 4,226 |

Table 5: Loss of life estimated with the HEC-FIA method (year 2000 population).

[6] Based on the population data of 2000 with totally 40.000 residents.




Fatalities - Overtopping with breach North West Sacramento River (OTNW)

Fatalities - Overtopping with breach Center Side of American River (OTSC)

Figure 32: Fatalities for the HEC-FIA method for the two scenarios.

### 3.3.4 Lifesim

Will be added when analyses become available

### 3.3.5 Loss of life comparison

In the previous sections 3.3.1 - 3.3.4 the outcomes of the loss of life analysis are reported. In this section a comparison between the outcomes obtained with the various methods is reported. Table 6 compares the life loss estimates for the four methods and the two scenarios.

| **Overview loss of life** | **Flood Scenario – Overtopping with breach** | | | |
|---|---|---|---|---|
| | *Sacramento River – North West* | | *American River – Center Side* | |
| Fatalities – no evacuation[7] | Absolute value | Average mortality | Absolute value | Average mortality |
| Interpolated 1953 method | 909 | 0.025 | 1811 | 0.045 |
| New Orleans method | 2815 | 0.08 | 1100 | 0.028 |
| HEC-FIA | 18412 | 0.46 | 4226 | 0.11 |
| Lifesim | PM | PM | PM | PM |

[7] Based on the population data of 2000 with totally 40.000 residents.

Table 6: Overview loss of life for all four methods

These estimates show the sensitivity of various methods for the pattern of flood depth and rise rates. For the flood scenarios considered in this case study, life loss estimates range between 900 and almost 18,000 fatalities. The total population in Natomas Basin considered in this case study is approximately 40,000 people, which is the year 2000 population. The average mortality ranges between 3% to 46 % of the total population. Since the registered population in 2010 is approximately over 100,000 people, the loss of life is expected to be 3 times as large. In section 3.5.3 the analysis for the 2010 situation is described with the use of the interpolated 1953 and New Orleans functions to determine loss of life for the year 2010.

In the interpolated 1953 method the mortality function includes both the effects of the maximum water depth and rate of rise, whereas the New Orleans method only includes the effect of the maximum water depth on the mortality. The HEC FIA approach results in very high mortality rates (90%) for large water depths (>5m) if no evacuation is assumed. Since large flood depths occur in the Natomas basin, for both scenarios the highest number of fatalities is obtained with HEC FIA.

*Flood scenario 1: Breach in the Northwest along the Sacramento River*
Flooding of the Sacramento River along the Northwestern section causes very high water depths (up to over 8.0 meter) in the densely populated area in the south of the basin and high rates of rise mainly in the northern area of Natomas Basin, close to the breach, which is not densely populated at all. Following from the flood characteristics, the New Orleans mortality functions compute a larger number of fatalities. The highest number of fatalities is obtained with HEC FIA, leading to more than 18,000 fatalities and a 46% mortality.

*Flood scenario 2*
The flood scenario of the American River has relatively moderate water depths to result and high rise rates in the densely populated area (southern Natomas Basin) in comparison with the flood scenario along the Sacramento River. Therefore the Interpolated 1953 method determines a higher mortality in the densely populated area than the New Orleans mortality function, with about twice as many fatalities. The highest number of fatalities is obtained with the HEC FIA method.

## 3.4 Evacuation analysis

In this section the results are discussed for (deterministic) scenario analyses for the Natomas region. Authorities can choose between different types of evacuation, depending on the situation at hand. In this chapter we primarily focus on preventive evacuation and discuss the potential of vertical evacuation.

This section discusses the results of evacuation using:

- HEC-FIA
- LIFESIM
- Evacuation Calculator

### 3.4.1 Evacuation with HEC FIA

Will be added when analyses become available

### 3.4.2 Evacuation with LIFESIM

Will be added when analyses become available

### 3.4.3 Evacuation with Evacuation Calculator

The Evacuation Calculator (EC) can be applied to calculate evacuation times. The travel process reflects the time that vehicles are on the evacuation road network. When a flood threat is detected several hours or days in advance, authorities may decide that the Natomas area is to be evacuated. However, when time is limited or a flood occurs unexpected authorities may decide that people need to take shelter on a safe (high) location in their homes or in public buildings. The effectiveness of evacuation is shown as a function of time starting at the onset of evacuation. Therefore, evacuation calculations were performed considering two different strategies:

1. Preventive horizontal evacuation: authorities advice the population to evacuate the Natomas area
2. Vertical evacuation: authorities advice the population to shelter at home (if possible)

#### *3.4.3.1 Data and assumptions for Evacuation modeling*

This chapter discusses the general data and assumptions for evacuation analysis with the different models.

*Population and zones*

The population data is based on the Census Group Blocks 2010[8] of Sacramento County and Sutter County. The area of Sacramento is divided into 53 blocks (in total 99,480 persons[9]). 4652 persons is the maximum number of people in a block. Sutter county (1000 persons) is represented as one block.

[8] Population: http://www.census.gov/geo/www/2010census/centerpop2010/blkgrp/bgcenters.html

Shapes: ftp://ftp2.census.gov/geo/pvs/tiger2010st/

[9] In the evacuation modeling the population data is based on the census data for the year 2010, whereas the loss of life estimates in the previous section are based on population data for the year 2000

In the evacuation calculation it is assumed that residents within a census group block evacuate from the centroid in the group block. Figure 33 presents an overview of the census group blocks in Natomas area. Inhabitants of Sutter County in Natomas are represented by only one group block. Figure 33 shows that the Sutter County census group block is partly located outside the Natomas area. This causes on overestimation of the true population in the Natomas area. Because population data on the level of Census Blocks is yet unavailable for 2010, the exact population overestimation is unclear. However, given that the Sutter County census group block represents 1,000 people, the maximum overestimation is less than 1% (1,000/ 100,480). Also we assume that people are at home when evacuation starts which is also uncertain (some might be at work, some might visit the area etc.).

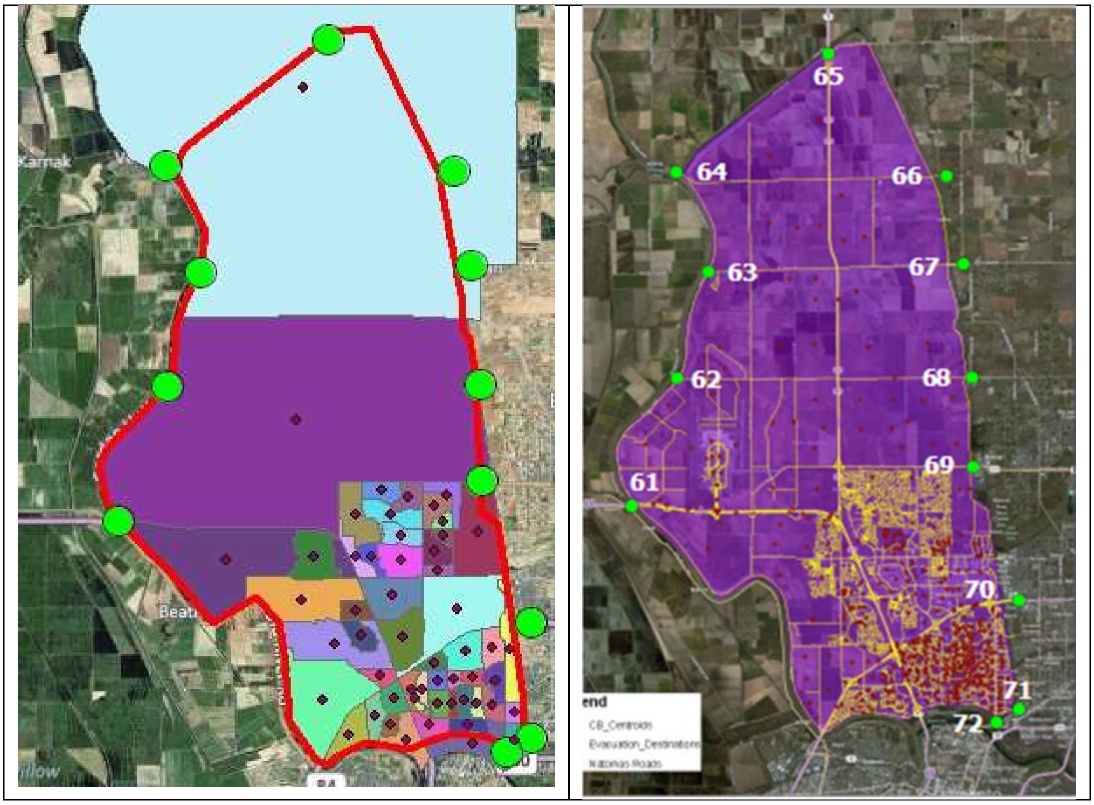



Figure 33: Left - Census group blocks in Natomas area and exit points (green dots). Right - road network. Exits 62, 63 and 64 are located on the river levee

### *Road network*

The road network of Natomas is used to develop the static model. Exit points are defined at the border of the Natomas area. When evacuees pass these exits they are assumed to be safe, however they need to travel on to a place to find shelter. Because of bottle necks and congestion on the network outside the Natomas area an outflow reduction factor is taken into account in the model.

The centroid of each zone is connected to the centroid of the nearest link of a road. The people in a zone will enter the road network at this location. Table 7 shows the capacity of the exit points which is taken into account.

| Centroid | FID | Street name | Free flow speed [mph] | Available Lanes | Capacity [vehicles per roadway per hour] | |
|---|---|---|---|---|---|---|
| 61 | 5461 | I 5 NB | 65 | 2 | 4600 | 2300 per lane |
| 62 | 3098 | W ELVERTA RD | 50 | 1 | 1600 | 1600 per lane |
| 63 | 4201 | RIEGO RD | 50 | 1 | 1600 | |
| 64 | 4185 | GARDEN HWY | 50 | 1 | 1500 | |
| 65 | 4221 | HWY 99 NB | 50 | 1 | 1500 | |
| 66 | 4196 | SANKEY RD | 50 | 1 | 1500 | |
| 67 | 4195 | RIEGO RD | 50 | 1 | 1600 | |
| 68 | 204 | W ELVERTA RD | 50 | 1 | 1600 | |
| 69 | 2909 | W ELKHORN BLVD | 50 | 1 | 1500 | |
| 70 | 2271 | I 80 EB | 65 | 3 | 6900 | 2300 per lane |
| 71 | 2482 | ARDEN GARDEN CONNECTOR | 50 | 2 | 3200 | 1600 per lane |
| 72 | 2078 | NORTHGATE BLVD | 50 | 1 | 1500 | |

**Table 7: Road capacities**

*Assumptions for evacuation settings*

In the reference situation the western exits 62, 63 and 64 are not taken into account. These exits are located on the river levee and therefore cannot be considered as safe evacuation destinations. The following parameter settings were applied to calculate evacuation times for the reference situation:

1. Non-response:
    a. Preventive horizontal evacuation: 10% of the population stays at home in the Natomas area
    b. Vertical evacuation: 90% of the population stays at home in the Natomas area
2. Departure Curve (DC): after 4 hours all inhabitants have left their homes and started to evacuate (except for the proportion non-response)
3. Persons per vehicle (PAE): on average there are 3 persons in one vehicle
4. Speed: vehicles travel with 12.5 mph (= 20 km/h)
5. Out flow factor: 0.2, i.e., road capacities on the exit points are 20% of the free flow capacity due to congestion.

### 3.4.3.2 Required time for evacuation

Figure 34 presents the results of the simulations. The figure compares the time needed for a preventive and a vertical evacuation. The difference between the travel time in these strategies a load equal to 80% of the population. In case of a vertical evacuation strategy congestion during the travel is so limited that the time needed for evacuation is almost equal to the departure curve, despite the strategy for evacuation. In case of a preventive evacuation the level of management matters as can be seen by comparing different strategies for evacuation. When people use the nearest exit some exits are heavily used (and overloaded) while other are not used. Traffic management which divides cars over the exits taking the capacity into account shows the upper limit.

Traffic management requires traffic measures in combination with clear communication to influence route choices of people.

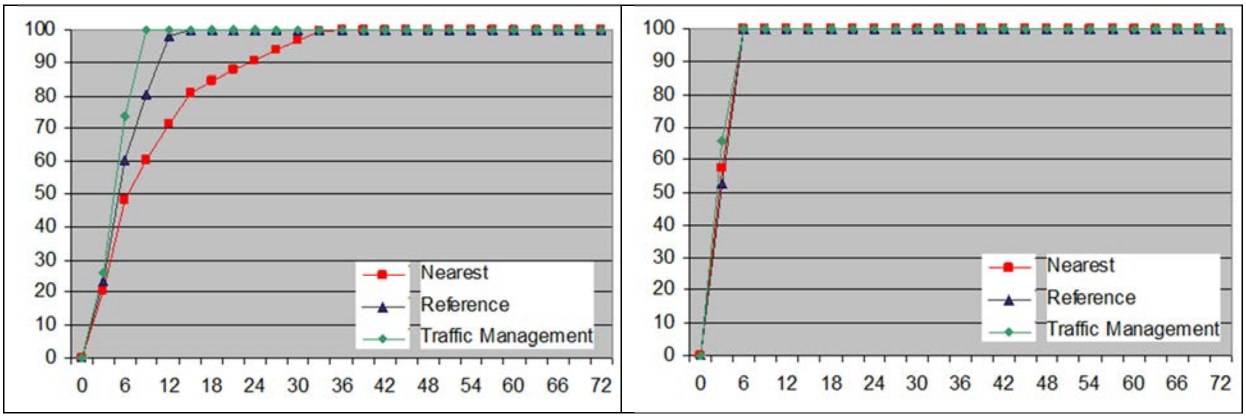



**Figure 34: evacuation curves (x axis the required time in hours and y axis the % of the number of people that succeeded in evacuation). Left: preventive horizontal evacuation strategy in the reference situation (without exits 62, 63 and 64). Right: evacuation curves for vertical evacuation strategy in the reference situation (without exits 62, 63 and 64).**

### *3.4.3.3 Sensitivity analyses*
### *Overview*

Varying the parameter settings for the different input parameters provides insight in the range of the time needed for evacuation resulting from either more pessimistic or more optimistic assumptions. The following table gives the parameter settings that were applied to calculate the variations in evacuation times (nine variations). In every run only one parameter is changed.

| **Parameter** | **Reference (ref)** | **Sensitivity analysis** | |
|---|---|---|---|
| Departure curve | 8 hr to 100% departure | 4 hr to 100% departure (DC) | |
| Persons per vehicle (PAE) | 3 | 2 (PAE2) | 4 (PAE4) |
| Driving speed | 12.5 mph | 5 mph (V5mph) | 20 mph(V20mph) |
| Unavailable exits | 0 | Most important exit unavailable[10] (Exit 1St) | Second most important exit unavailable[11] (Exit 2nd) |
| Congestion (outflow factor) | Outflow factor 0.2 | More congestion Outflow factor 0.1 (OF1) | Less congestion Outflow factor 0.3 (OF3) |

**Table 8: Overview of the parameter settings in the sensitivity analyses. In every sensitivity calculation only one parameter is changed.**

[10] Modeling setting, Nearest exit: without exit 69; Modeling setting, Traffic management: without exit 70

[11] Modeling setting, Nearest exit: without exit 70; Modeling setting, Traffic management: without exit 61

The sensitivity as a function of time is shown in Figure 35 (all scenarios with traffic management strategy reference), Figure 36 (all scenarios with traffic management as a strategy) Figure 37 (all scenarios with traffic management strategy nearest exit). The results show that the used traffic management strategy strongly influences the effectiveness of evacuation. The results also show the importance of the element time. Given the steep slopes of the curves, a few hours less available will reduce the evacuation effectiveness far more than the parameters in the sensitivity analyses. For Natomas it is shown that all parameters related to the traffic load (as the number of people in a car, and therefore also the number of people in the area) as well as the outflow factor are more sensitive parameters. The departure curve is shown not to be very sensitive. This is discussed in the next chapter.

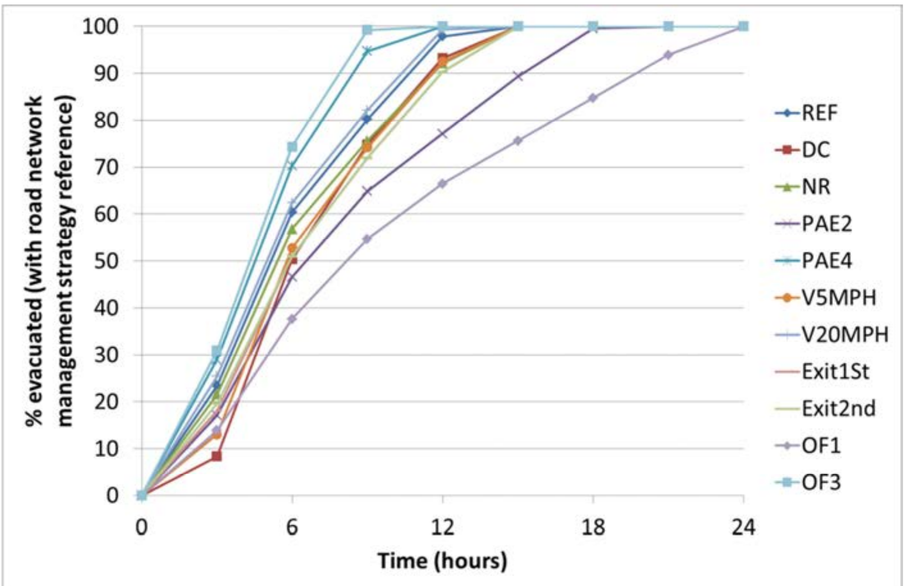



**Figure 35: Sensitivity analyses – required time for evacuation for road network management strategy reference (medium strategy)**

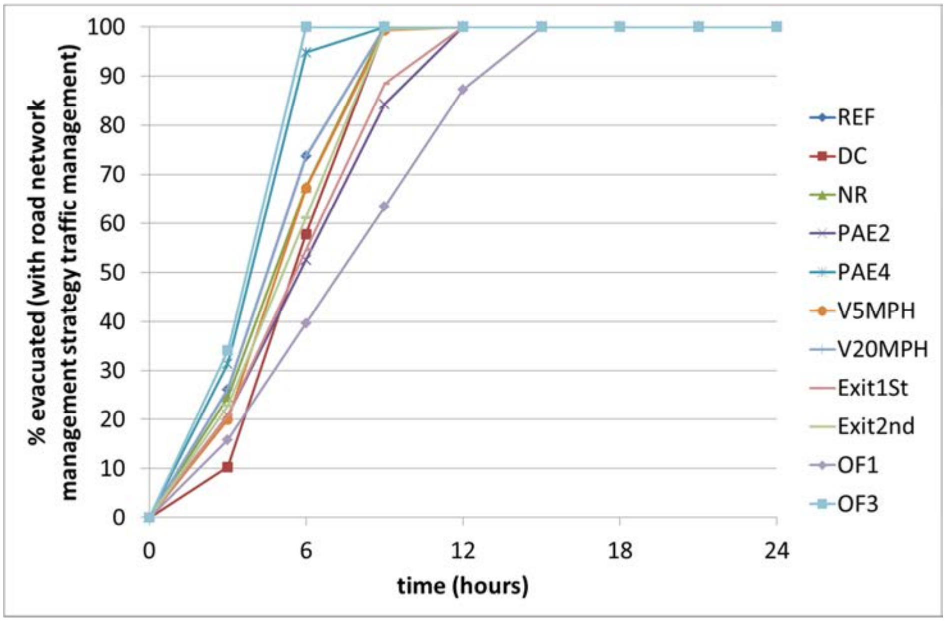



**Figure 36: Sensitivity analyses – required time for evacuation for road network management strategy traffic management (optimistic strategy)**

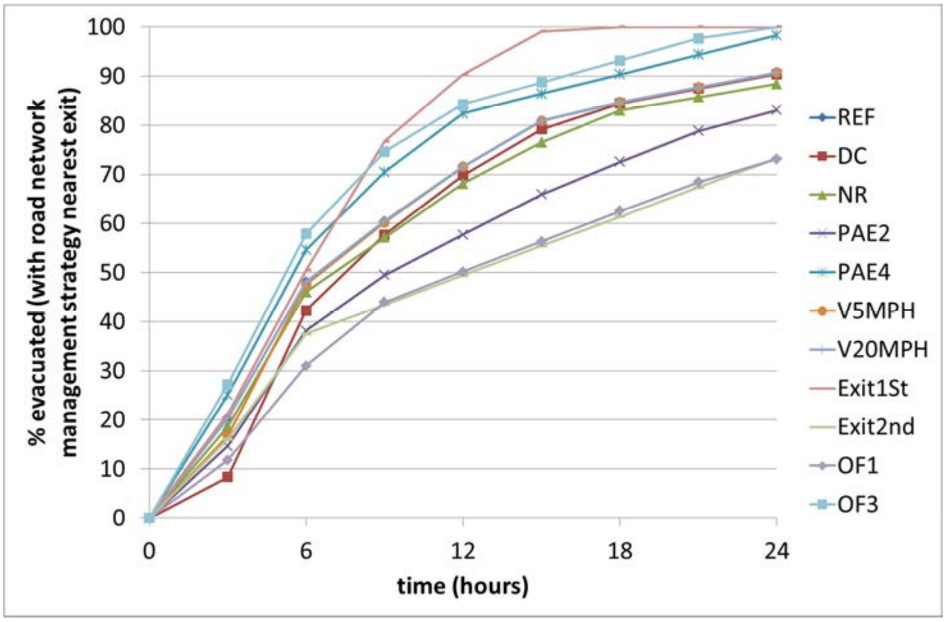



Figure 37: Sensitivity analyses – required time for evacuation for road network management strategy nearest exit (pessimistic strategy)

### *Departure curve*

Figure 38 shows the departure curve used for Natomas by USACE. The total time for departure is more than 4 hours.

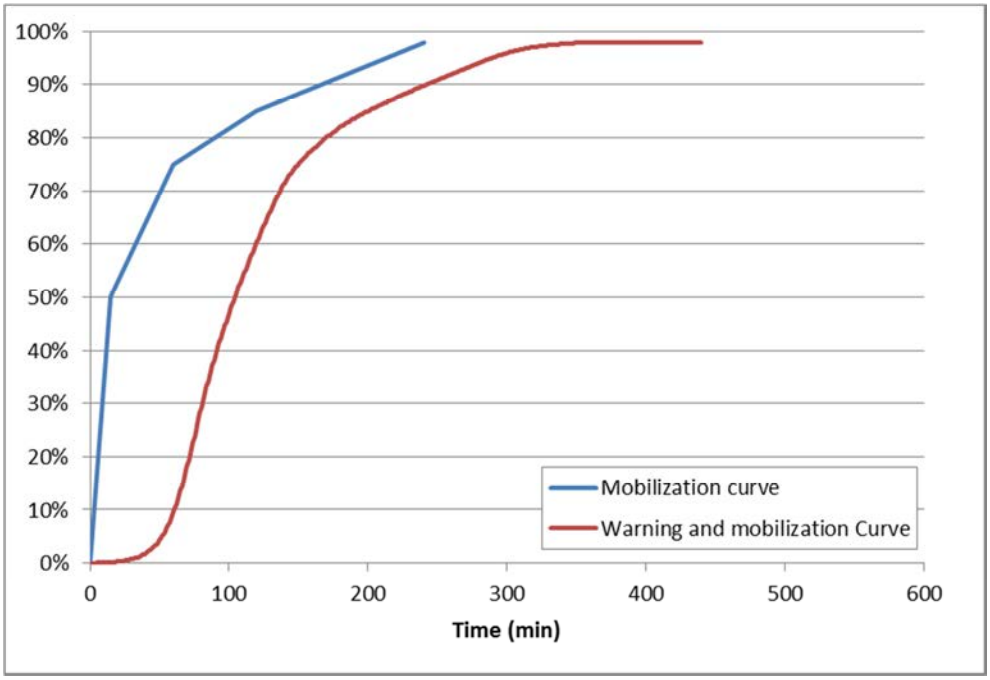



Figure 38: Departure and mobilization curve used in Natomas with HEC FIA.

Figure 39 shows the difference in required time in our model for preventive evacuation when the departure curve is varied from 4 to 8 hours. It is shown that the time needed for total evacuation is hardly influenced. Only in the first hours of evacuation the departure curves influences evacuation (the road capacity is not used optimal in the beginning of the evacuation).

Although it is important to warn and mobilize people quickly it is shown that measures to reduce the warning and mobilization time are not effective to increase horizontal evacuation. However when time is limited the warning and mobilization can increase the effectiveness of vertical evacuation and citizen's response and therefore reduce loss of life.

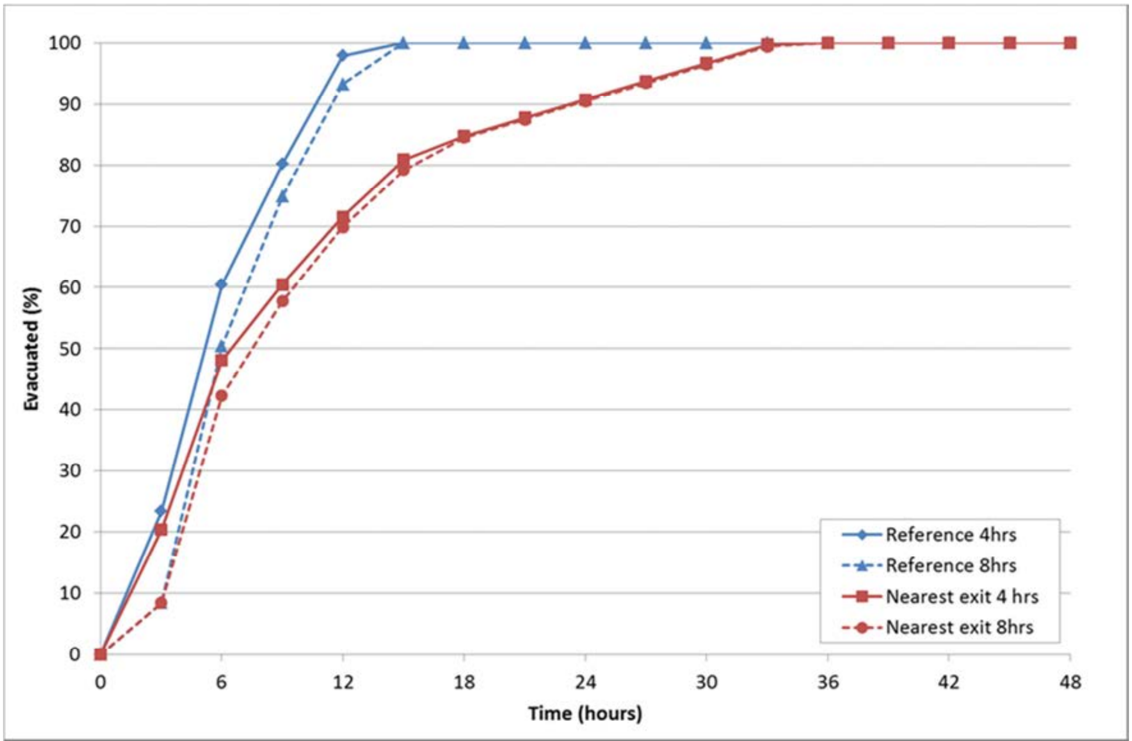



Figure 39: Impact on percentage of people evacuated when using a departure curve of 8 hours instead of 4 hours.

### 3.4.4 Discussion and comparison of outcomes various evacuation models

Will be added when HEC FIA and Lifesim results become available.

## 3.5 Exploratory / additional analyses

In this section we discuss a number of additional analyses that are intended to show how certain techniques / approaches can be applied in the US context and to Natomas basin. Section 3.5.1 presents some preliminary ideas for a risk to life analysis. The next section presents the results of the EvacuAid model for the Natomas Basin to support evacuation and emergency planning decisions.

### 3.5.1 Conceptual ideas for risk analysis for Natomas Basin

#### *3.5.1.1 General approach*

In the Netherlands, risks to life are quantified as part as ongoing policy studies, such as VNK and the Delta program.

The general approach for determining the flood risk for an area is to identify a set of scenarios and asses the probability of flooding (P) and the consequences for these scenarios. To determine the flood risk for an area, an overview of the possible scenarios has to be defined. For the Natomas basin the following schematic fault tree is given with the possible scenarios with respect to breach location, failure mode and evacuation effectiveness. For a more complete risk analysis other locations, breaching scenarios and various "evacuation scenarios" would have to be analyzed and

this is a topic for further investigation. Here, the principles of the risk analysis are illustrated on the basis of the two scenarios that have been analyzed in previous sections of this report (in bold lines).

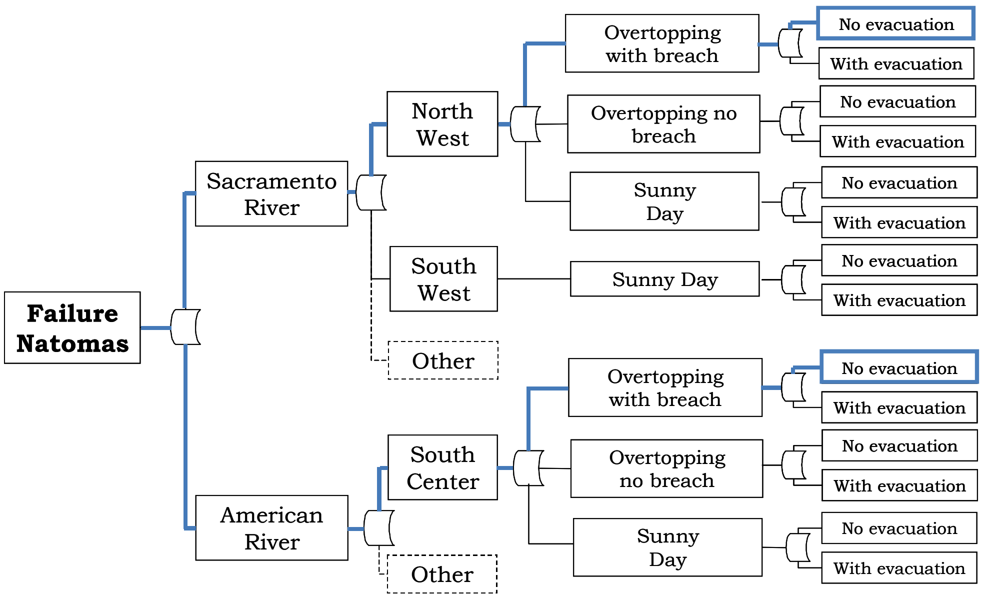



Figure 40: Schematic Fault tree for the Natomas Basin

For each of the possible scenarios a probability of occurrence and consequences in terms of economic damage and loss of life have to be determined. When this information is available the flood risk per scenario can be determined, combining the risk calculations per scenario gives the total risk for the area.

The flood risk can be expressed in different risk metrics, for instance an expected value of the loss of life or the spatial distribution of the individual risk over the area.

#### *3.5.1.2 Failure probability estimation based on fragility curves*

There are different methods to determine the failure probability. Ideally, one would want to do a full probabilistic analysis including water level statistics, failure modes, levee characteristics including spatial distributions and uncertainties.

One of the more simplified methods is using fragility curves in combination with the exceendence probabilities of water levels. To come to a first and crude approximation of probabilities for the two flood scenarios, existing information is used and combined. For the two solid blue line scenarios in Figure 41, the failure probability is estimated based on available fragility curves and water level exceedance curves.

For different segments (reaches) along the levee system of the Natomas basin fragility curves have been developed (USACE, Dec 2010). The figure below show the different reaches along the levee system, the two scenarios considered in this analysis are situated in reach C and I.

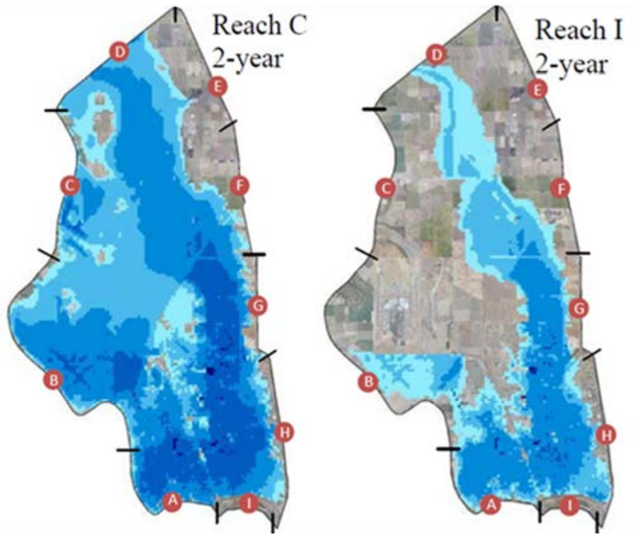



Figure 41: Overview reaches for the Natomas basin (USACE, 2010).

The fragility curves for reach C and I are given in Figure 42[12]. The fragility curves show a failure probability given a certain water level. When combined with the exceedence frequency of the water levels the failure probability can be determined.

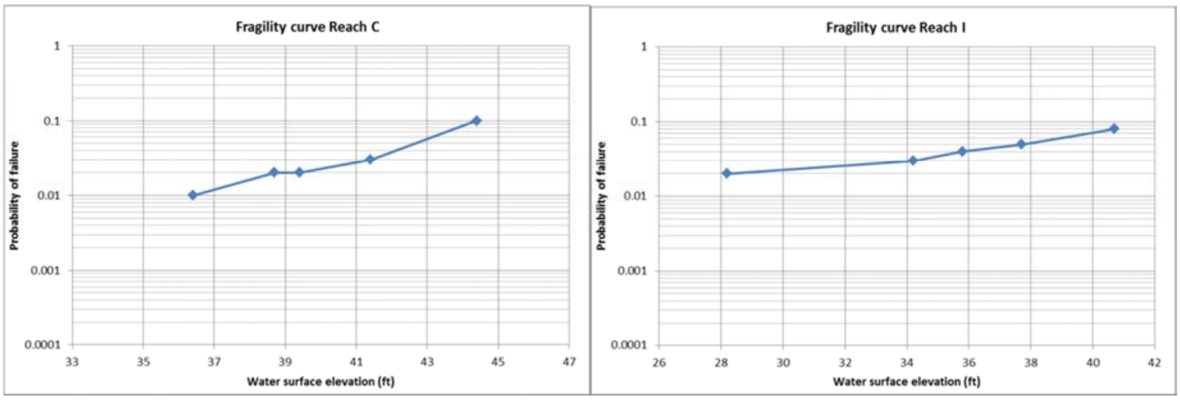



Figure 42: Fragility curves (USACE, 2010)

The following two figures give the exceedence frequency of the water levels (MBK Engineers, 2009). The dashed line is the extrapolation of the exceedence frequency for the lower and higher water surface elevation.

[12] The fragility curves show the situation with the projects, see USACE, Dec 2010 for more detailed information.

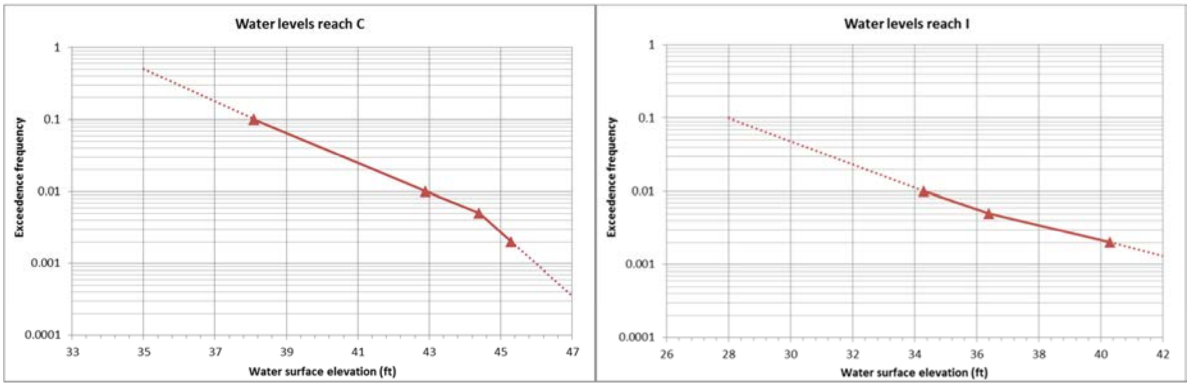



**Figure 43: Exceedence frequency of water levels, based on (MBK Engineers, 2009).**

When the data from the fragility curve and the exceedence frequency is combined Figure 44 can be created. The surface under the graph is the failure probability of that reach.

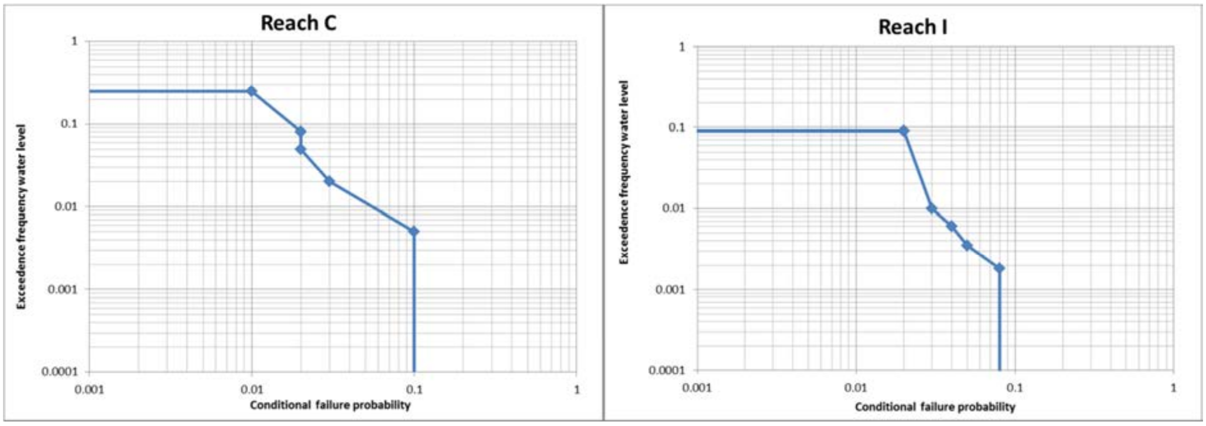



**Figure 44: Combination of fragility curve and exceedence frequency of the water levels.**

By determining the surface under the two graphs the failure probability for reach C is approximately 1/150 year and for reach I the probability of failure is 1/270 year. These probabilities can be used to determine the flood risk by multiplying these probabilities by the consequences in terms of mortality or loss of life. For a better and more complete analysis of failure probabilities, further investigation is recommended.

#### *3.5.1.3 Overview of loss of life estimates*

The loss of life estimations for the interpolated 1953 and NOLA mortality functions for the two scenarios is described in section 3.2 and 3.3.

#### *3.5.1.4 Risk calculation*

The flood risk can be expressed in different risk metrics. In this section three risk metrics for risk to life will be discussed and calculated on the basis of the results for the two breaching scenarios. This is an incomplete characterization of the risk, for illustration purposes of the approach only. In order to estimate the risk the flooding probability estimates are combined with life loss estimates that have been presented in section 3.2. Here, we applied the life loss estimated for the New Orleans mortality functions. These resulted in estimates of 2815 fatalities for breaching in the northwest and 1100 fatalities for breaching in the south. The same approach can be applied for the interpolated 1953 functions but that has not been done in this section.

### *Individual risk*

The individual risk is defined as the probability of loss of life of an average, unprotected person that is constantly present at a given location. To determine the individual risk the mortality at a certain location due to a scenario has to be multiplied by the probability of that scenario. This has to be done for all possible scenarios. When combining all scenarios the individual risk for the area can be determined.

$$IR(x,y) = \sum_i P_i F_{D,i}(x,y)$$

Where: IR(x,y) – individual risk at location (x,y); $P_i$ – probability of scenario I (per year); $F_{D,i}(x,y)$ – mortality at location x,y for scenario i.

In this analysis only two scenarios are considered for illustration purposes. The first step is to determine the individual risk per scenario, by multiplying the mortality per scenario with the probability per scenario. This results in the following two risk maps per scenario.

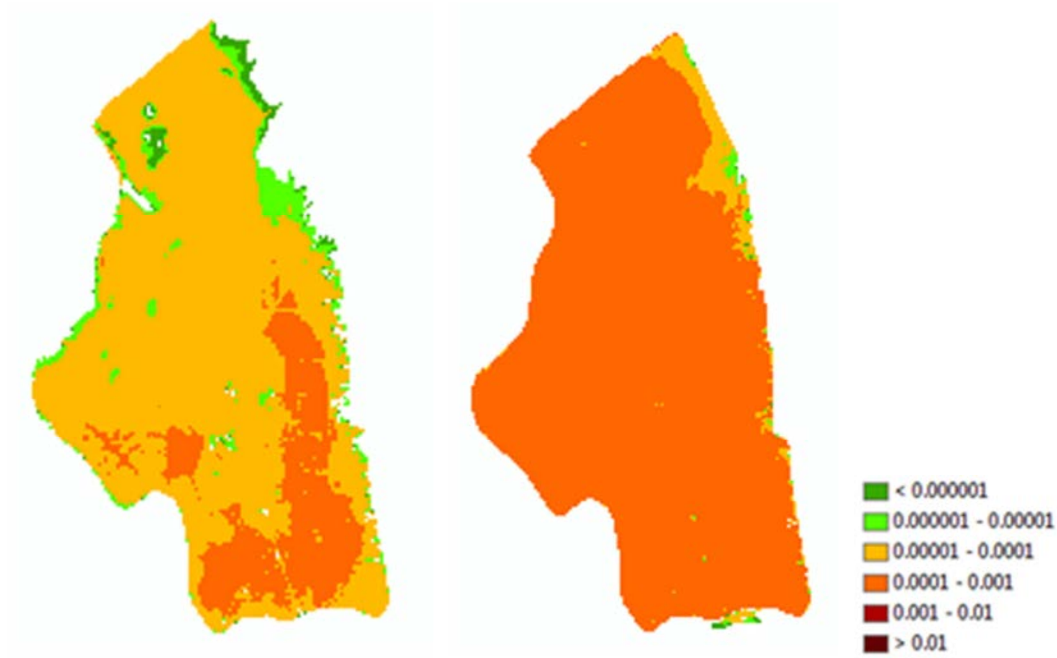



**Figure 45: Individual Risk per scenario, Left Reach I and Right Reach C.**

The two individual risk maps combined gives the total individual risk for the Natomas area, Figure 46. For most of the area, individual risk is higher than $10^{-4}$ per year. In further work, more scenarios can be added. Also, an alternative definition of individual risk can be used in which evacuation effectiveness is included. In that case, the evacuation also affects the individual risk.

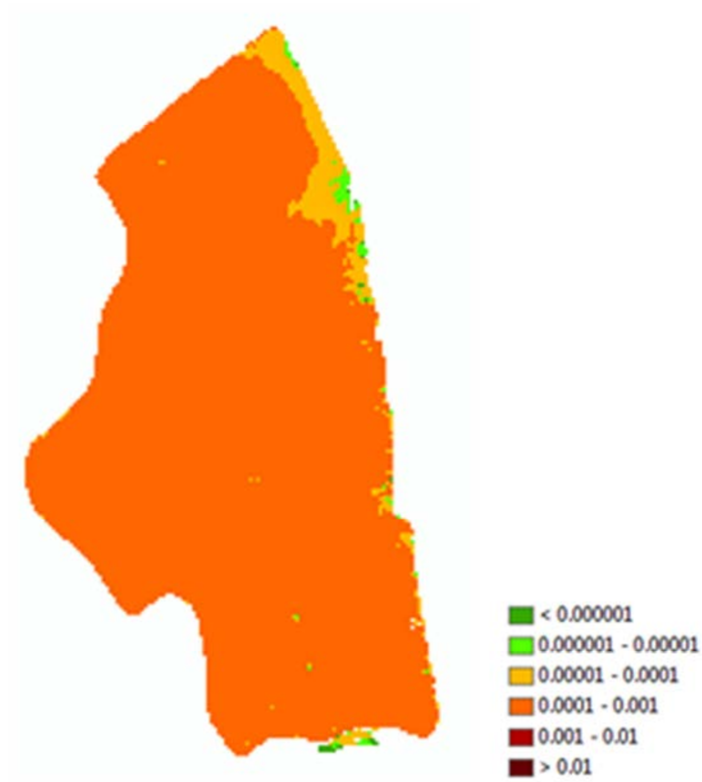



Figure 46: Individual Risk for the Natomas basin, based on two scenarios.

### *Societal risk*

The societal risk concerns the probability of an accident with a large number of fatalities. This risk metric shows all individual scenarios in a graph. This gives insight in the loss of life of a flood scenario and the probability of exceedence of that scenario. For a complete characterization of societal risk various flood and evacuation scenarios would have to be analyzed. Based on the probability distribution of these life loss events and FN curve can be constructed. In this analysis only two scenarios are considered so that graph only consists of two that describes a small part of the societal risk.

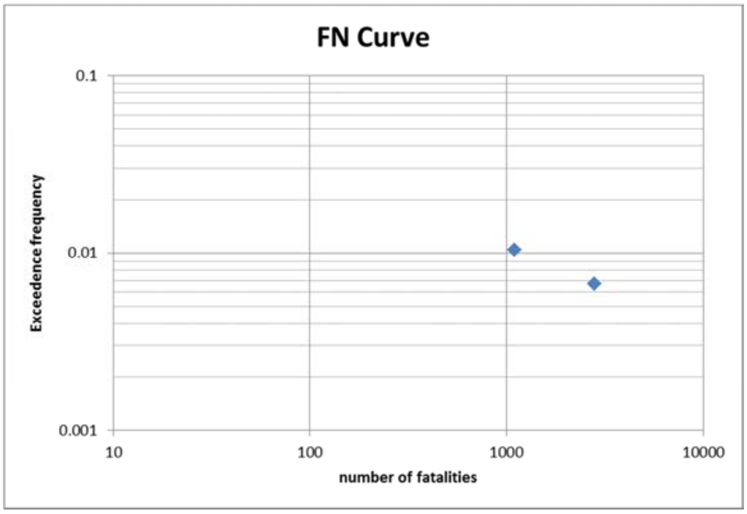



Figure 47: Societal risk for the Natomas basin.

*Expected value of the number of fatalities*

The expected value of fatalities describes the average number of fatalities weighted by the probabilities of the scenarios. This value is the surface under the societal risk curve. Considering the two scenarios in this analysis the expected number of fatalities is; 1/150 * 2815 + 1/270 * 1100 = 23 fatalities per year.

### 3.5.2 Application of EvacuAid to the Natomas Basin

EvacuAid defines the expected number of people that can evacuate over time and the loss of life in case of a flood for different strategies for evacuation. The method EvacuAid can take uncertainties into account. For each scenario of the sensitivity analyses with the Evacuation Calculator (EC) (including the form of traffic management) the probability of these scenarios can be taken into account[13]. For each scenario in the sensitivity analyses it is defined how it is related to citizen's response, authority response or measures related to the use of infrastructure. This gives the opportunity to make an assessment for the effectiveness of measures.

#### *3.5.2.1 Number of people evacuated*

Figure 48 shows the expected number of people that can evacuate preventive out of the Natomas basin taken all scenarios of the sensitivity analyses and the probability of them into account. The expected result of evacuation over time is shown in Figure 48 for the three network-management strategies in HIS-EC (nearest exit, reference and traffic management). Also the overall expected value for evacuation is shown.

Using knowledge of the actual conditions of citizen's response, authority response measures can be considered to influence these parameters. When measures are implemented the effectiveness of evacuation increases as shown Figure 49. By changing the value of the parameters the probability of the underlying scenarios is changed. Therefore the expected value of evacuation changes between the boundaries of the available scenarios. Figure 49 also shows a bandwidth with an upper and lower limit (the dotted line). The upper and lower limit is based on the maximum and minimum conditions of the parameters in EvacuAid. It is shown that some scenarios are outside the bandwidth, these scenarios are very optimistic or pessimistic and have a limited probability compared to others.

[13] For the pilot application for Natomas we used probabilities developed for evacuation of large scale areas in The Netherlands (see Kolen et al 2012). The results show the potential for Natomas or other areas. To be used in real practice the probabilities have to be based on (local) experts.

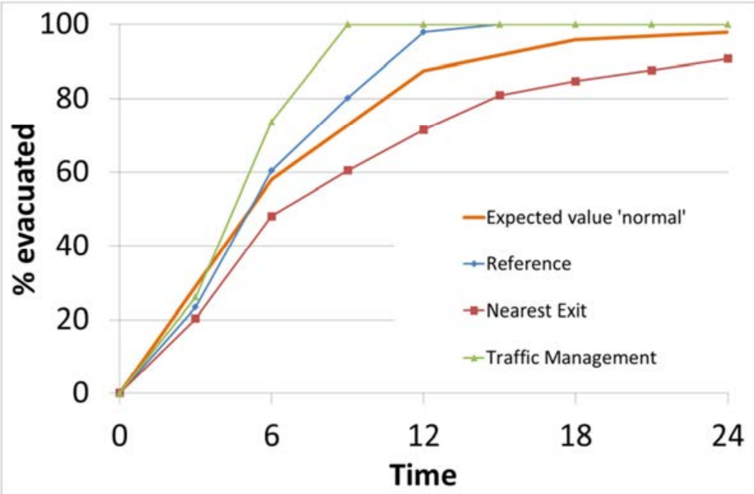



Figure 48: Expected number of people that can evacuate.

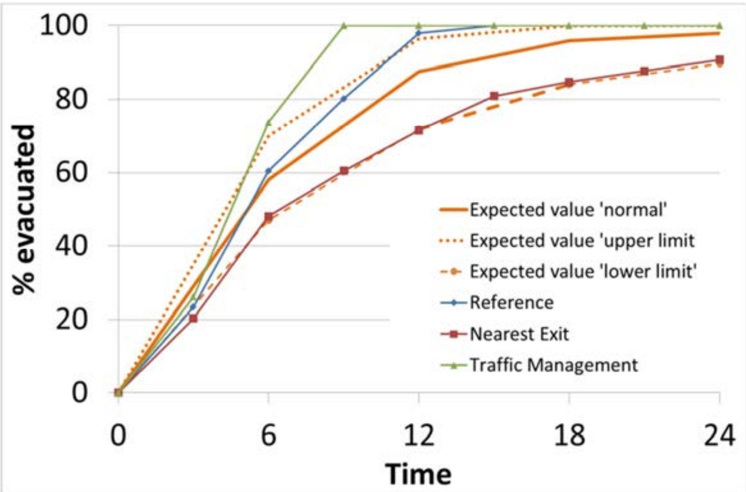



Figure 49: Expected value for upper limit ort lower limit.

The results for vertical evacuation can be analyzed by EvacuAid as well. However as is already shown in Figure 34 the required time evacuation (in case of a strategy for vertical evacuation it is considered that some people evacuate horizontal because of non-compliance) is almost equal to the departure curve for all road network management strategies. This is caused by the local circumstances of the Natomas area (number of people and the capacity of the road network). The impact of uncertainties for the number of people that van evacuate as a function of time is limited and not further explored, the next chapter discusses the relation with loss of life.

### *3.5.2.2 Loss of life for preventive and vertical evacuation*

EvacuAid also compares the expected loss of life in case of different strategies for evacuation as a function of time of being exposed to a flood. In this research we improved the method EvacuAid. We added the loss of life functions of New Orleans to EvacuAid. The functions of New Orleans describes loss of life related to all people in an area exposed to flooding considering the water depth in this area. The use of these functions are considered as an improvement to the default estimations of loss of life in EvacuAid which relates the number of people at a location to an average mortality rate. By the improvement the water depth is also taken into account. Further improvements can be made to relate the mortality function to a grid of water levels that replace the average water level in an area.

- People in a shelter
- People at home which are prepared
- People at home which did not made additional preparations
- People hit during evacuation.

The number of people which can evacuate preventive is taken into account as well, the mortality rate for them is equal to mortality rate for car accidents.

Using the mortality functions of New Orleans we defined mortality functions for the different locations of EvacuAid by increasing or decreasing the function by a factor (Table 9). The mortality functions are applied to an average water level in theNatomas area.

| **Location** | **Factor**<br>**(Factor * mortality function)** |
|---|---|
| At home not prepared | 1 |
| At home prepared | 0.2 |
| Shelter | 0.1 |
| Hit while in traffic | 5 |

Table 9: Factors increasing and decreasing the mortality function.

When this implementation is applied to the Natomas case study the following results in terms of loss of life are calculated, Figure 50. The dilemma point is approximatley 20 hours in advance of the levee breach. When the available time for evacuation (this available time is without time for decision making and preparation) is less than 20 hours a horizontal evacuation is expected to result in more loss of life than vertical evacuation. When more time is available a horizontal evacuation is expected to result in less loss of life. Measures related to the parameters of evacuation (citizen response, authority reponse, use of infastructure and time needed for decision making) can influence the moment of the dilemma point. Measures related to decrease mortaility rates also influence the moment of the dilemma point, when for example measures are taken to increase the resilience of people in a shelter the mortality will decrease.

The figure also shows an increase in loss of life between 0 and 6 hours in case of horizontal evacuation This is because the number of people travelling increases. After time more people leave the area and loss of life decreases. In case of vertical evacuation loss of life reduces in the first hours because some people leave the area. After time the loss of life becomes constant because most people reached their destinations in shelters etc.


Figure 50: Indication of loss of life as a function of time for preventive and vertical evacuation.

### 3.5.3 Loss of life estimation for the Natomas area for the year 2010

In the previous sections the analysis of the Natomas basin has been done for the year 2000. The population increased significantly from the year 2000 to 2010, from 40,000 people in 2000 to over 100,000 in 2010. This increase in population has no influence on the mortality rates caused by the different scenarios but has a major impact on the number of fatalities. In Figure 51 the distribution of the population over the Natomas basin is shown. The majority of the increase in population is located in the southeastern part of the basin.

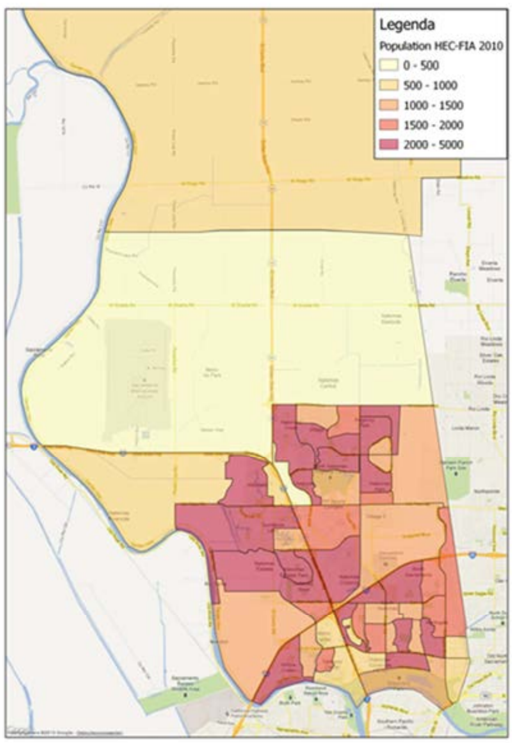


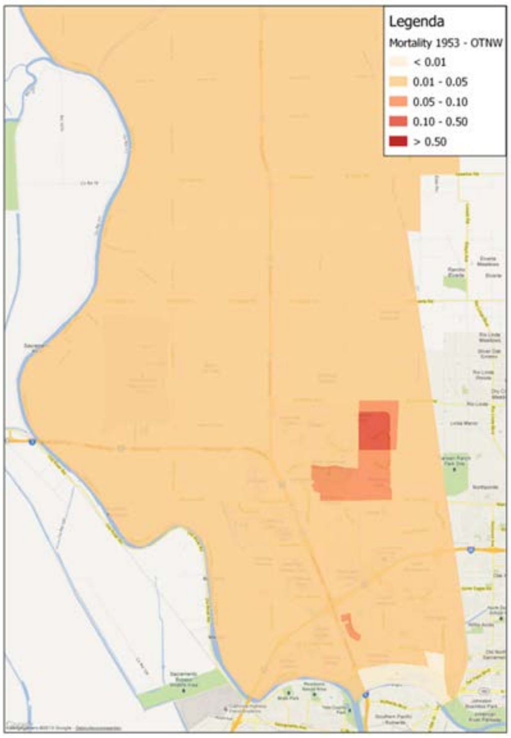

Figure 51: The 2010 population for the Natomas basin (source: US 2010 Census).

Because the population data for the year 2010 is only available on a blockgroup level the loss of life analysis has also been done on this aggregation level. The mortality rates have been averaged over a blockgroup level and also the number of fatalities is given per blockgroup.

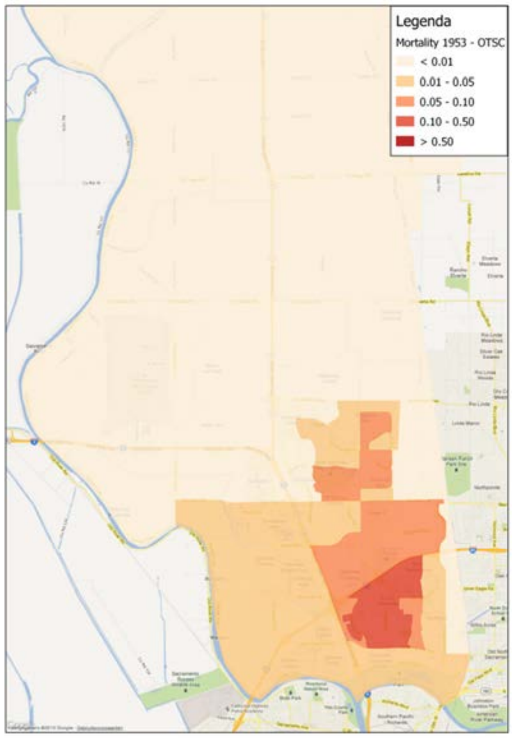
For this 2010 loss of life analysis the same flood scenarios have been used as in the Natomas case study in the previous sections.

#### *3.5.3.1 Interpolated 1953 method*

In sections 3.2 and 3.3 the scenarios have been described and the mortality has been determined. To analyze the 2010 situation the mortality rates for the two scenarios have been aggregated to the blockgroup level.




Mortality - Overtopping with breach
North West Sacramento River (OTNW)




Mortality– Overtopping with breach
Center Side of American River (OTSC)

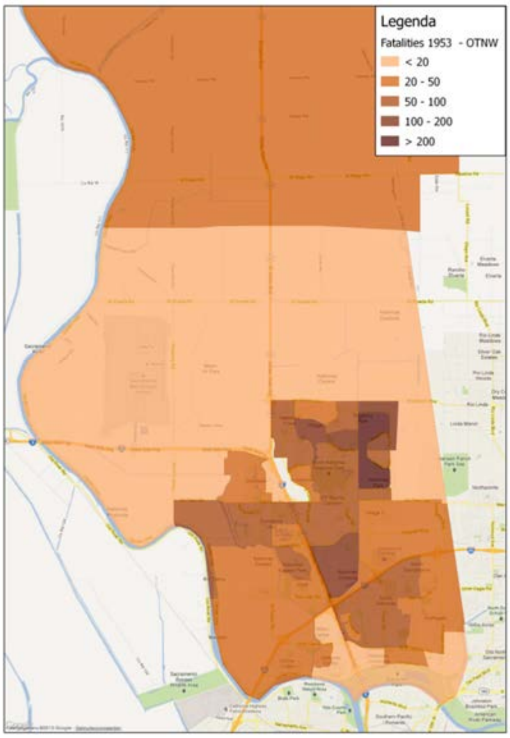
Figure 52: Mortality for the interpolated 1953 functions for the two scenarios on a blockgroup level.

Table 10 shows the results of the loss of life analysis based on the interpolated 1953 method for the 2010 and 2000 situation. This table shows that the number of fatalities increases by a factor 2.5 -3 due to population growth in the Natomas basin.

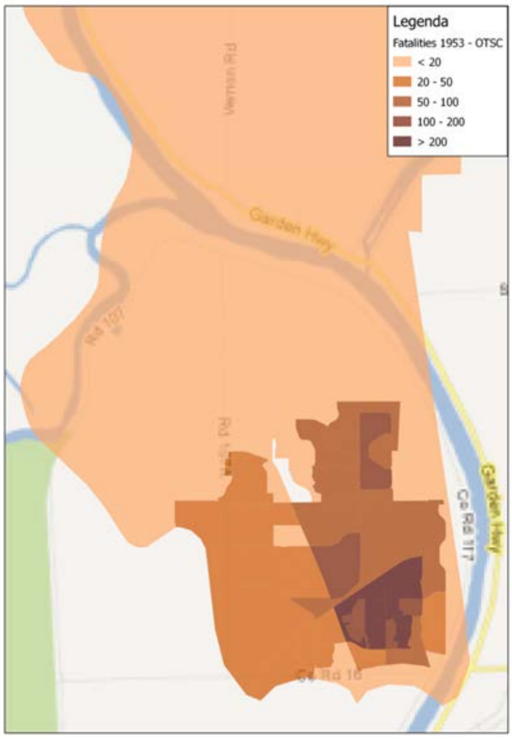
| **Interpolated 1953 method** | **Flood Scenario – Overtopping with breach** | |
|---|---|---|
| | Sacramento River – North West | American River – Center Side |
| Fatalities 2000 (grid cell level) | 910 | 1810 |
| Fatalities 2010 (blockgroup level) | 3100 | 4460 |

Table 10: Overview number of fatalities in case of a overtopping with breach for the two breach locations.

In Figure 53 the spatial distribution of the fatalities is shown. When compared with the 2000 situation there is a significant increase in fatalities in the newly build residential areas north of the I-80.




Fatalities - Overtopping with breach
North West Sacramento River (OTNW)




Fatalities – Overtopping with breach
Center Side of American River (OTSC)

**Figure 53: Fatalities for the interpolated 1953 functions for the two scenarios on a blockgroup level.**

### *3.5.3.2 New Orleans method*

In sections 3.2 and 3.3 the scenarios have been described and the mortality has been determined. To analyze the 2010 situation the mortality rates for the two scenarios with the New Orleans method have also been aggregated to the blockgroup level.

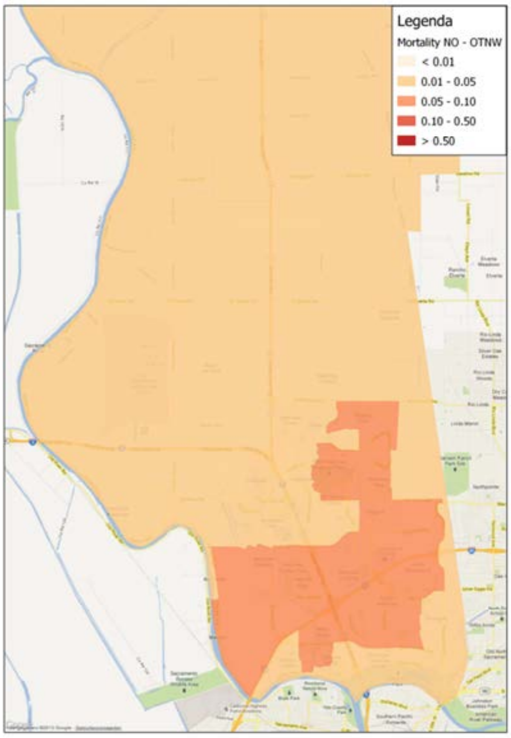
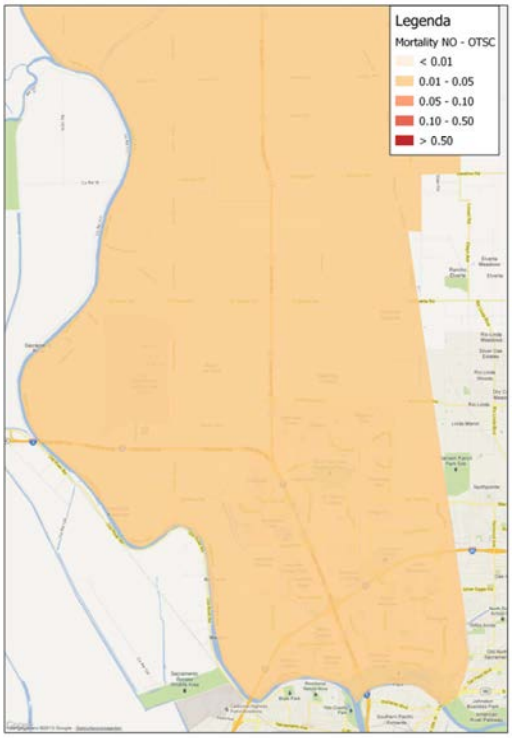
| | |
|---|---|
|   |   |
| Mortality - Overtopping with breach<br>North West Sacramento River (OTNW) | Mortality– Overtopping with breach<br>Center Side of American River (OTSC) |

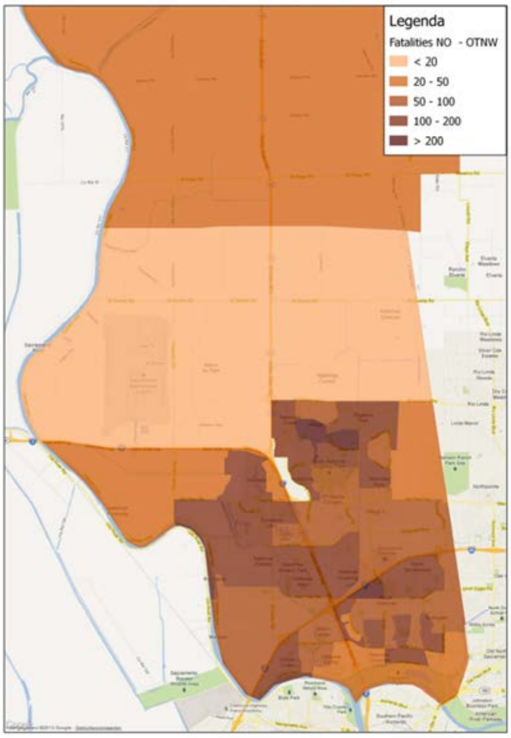
**Figure 54: Mortality for the New Orleans functions for the two scenarios on a blockgroup level.**

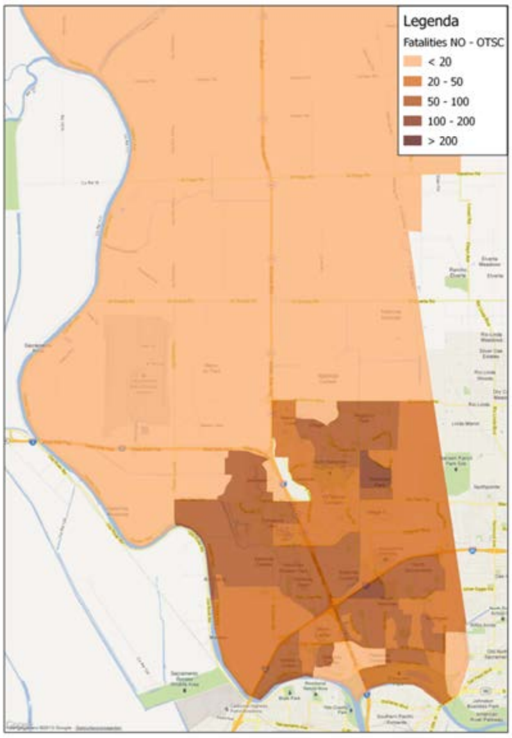
Table 11 shows the results of the loss of life analysis based on the New Orleans method for the 2010 and 2000 situation. This table shows that the number of fatalities increases by a factor 2 – 2.5 due to population growth in the Natomas basin.

| **New Orleans method** | **Flood Scenario – Overtopping with breach** | |
|---|---|---|
| | Sacramento River – North West | American River – Center Side |
| Fatalities 2000 (grid cell level) | 2810 | 1100 |
| Fatalities 2010 (blockgroup level) | 5160 | 2860 |

**Table 11: Overview number of fatalities in case of a overtopping with breach for the two breach locations.**

As for the interpolated 1953 method in the New Orleans method the spatial distribution of the fatalities show a significant increase in fatalities north of the I-80.




| Fatalities - Overtopping with breach North West Sacramento River (OTNW) | Fatalities – Overtopping with breach Center Side of American River (OTSC) |
|---|---|

**Figure 55: Fatalities for the New Orleans functions for the two scenarios on a blockgroup level.**

# 4 Herbert Hoover Dike case study

## 4.1 General area description / overview

The Herbert Hoover case study area is situated south of lake Okeechobee and is an area that is mainly used for agricultural activities. The residential areas in the area are the city of Clewiston and Belle Glade.


Figure 56: Herbert Hoover case study area.

## 4.2 Data and assumptions

This section outlines the used data and made assumptions in the loss of life analysis, with respect to the flood scenarios (section 4.2.1), flood maps (section 4.2.2) and population data (section 4.2.3).

### 4.2.1 Flood scenarios

Along the levees surrounding lake Okeechobee different flood scenarios can be defined. In (USACE, 2011b), different reaches have been defined where possible flood scenarios can occur, Figure 57. In this case study only the reaches 2 and 3 are included in the analysis. For these two reaches two different breach scenarios are taken into account, one scenario with a lake level of 20 feet and one with a lake level of 30 feet. For a full scale risk analysis for the area other reaches have to be included and other hydraulic loads have to be included.

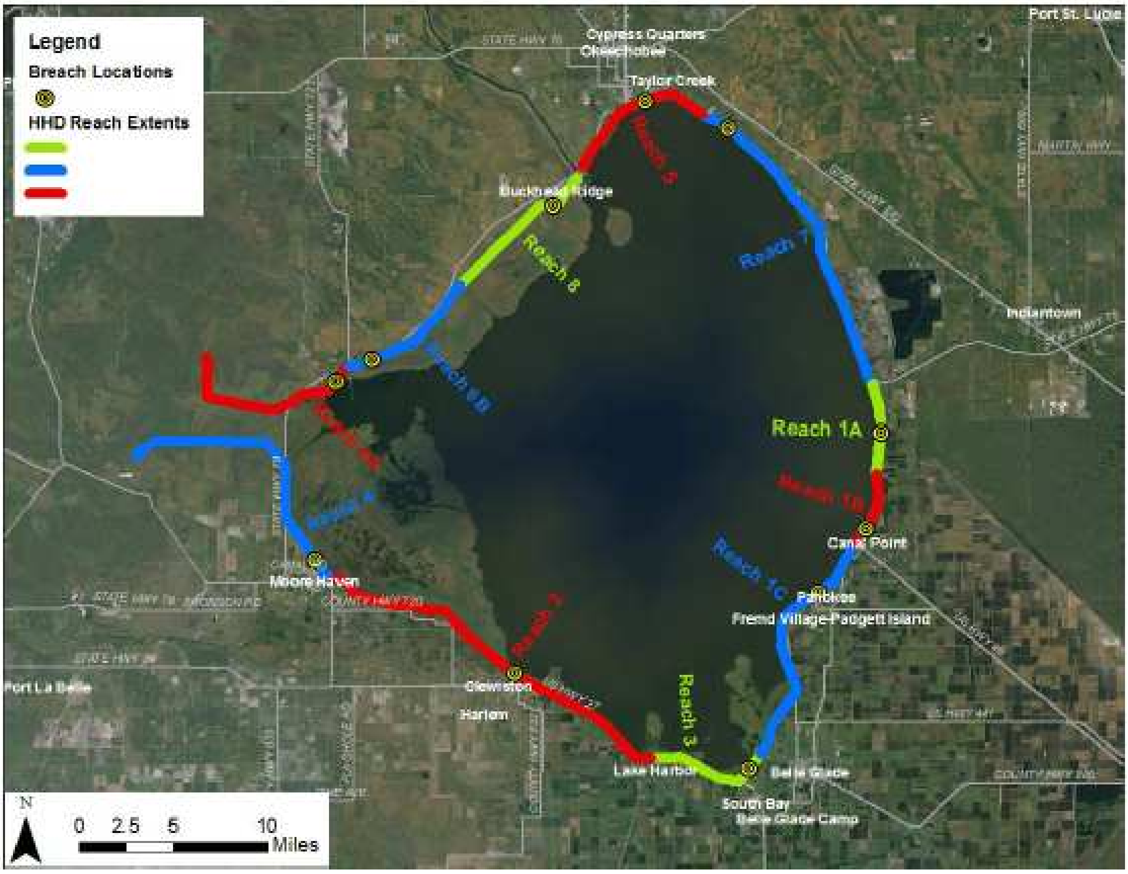



Figure 57: Flood scenario reaches, (Source: USACE, 2011b).

### 4.2.2 Flood maps

A 2-dimensional flood model can describe each possible flood scenario by its flood characteristics. The flood characteristics exist of spatial distribution of the water depth, flow velocity, rate of rise, time of arrival and time of departure. The flood characteristics can be presented by flood maps, which are the input files for the loss of life analysis. The following flood characteristics determine the mortality rate in the various models:

- max water depth [m]
- max velocity [m/s]
- rate of rise [m/hr]

The extent of the flood depends on multiple input parameters, e.g. water level, breach development, duration of the flood event, elevation surface level (terrain model), roughness factor.

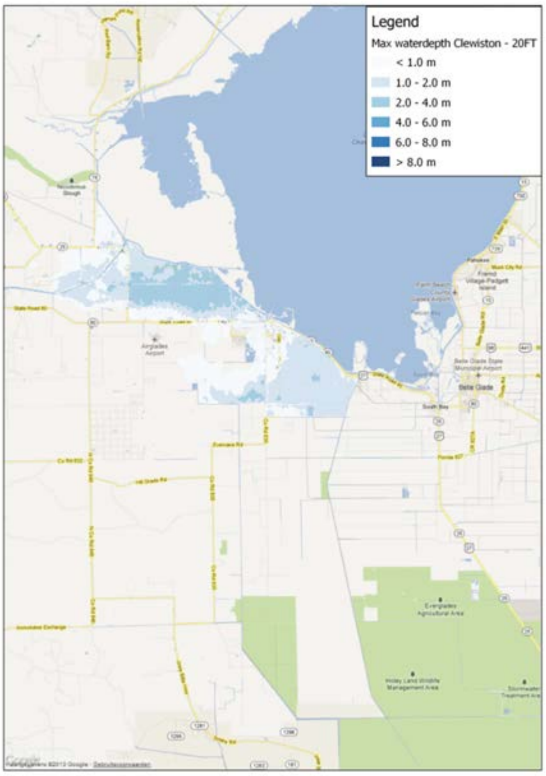
This section shows the flood maps of both flood scenarios (source: flood characteristics provided by USACE, 2011b). This flood maps are input files for the loss of life analysis. The loss of life functions of Jonkman [Jonkman S.N. (2007)] are based on flood data in meters. Therefore the provided flood data are converted from feet to meters.

In the following table information on height and elevation differences is given on the breach locations.

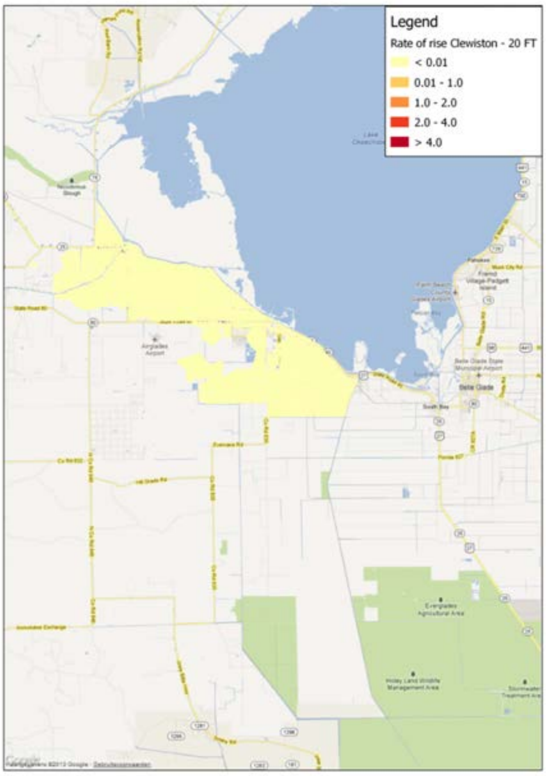
| Breach locations | Crest elevation of levee (ft – NAVD) | Toe elevation of levee (ft – NAVD) | 20 FT head difference (ft) | 30 FT head difference (ft) |
|---|---|---|---|---|
| Clewiston (location 2) | 32 | 11.5 | 8.5 | 18.8 |
| Belle glade (location3) | 41 | 7.2 | 12.8 | 22.8 |

Table 12: Overview of elevations on the two breach locations (Source: USACE, 2011b).

In the following figures the two flood scenarios for the Clewiston area are shown. The big difference between the 20 and 30 feet scenario is the size of the flooded area. This is due to the many canals and small levees that influence the flood pattern. The maximum water depth in the city of Clewiston is approximately 4 meters. In both scenarios the rise rates are relatively small, less than 0.01 m/hr. Also, flow velocities for the scenarios are low (less than 1 m/s) for both scenarios, so that flow velocities do not affect mortality. The low rise rates and velocities likely due to the effects of the canals in front of the levee, that slow down and disperse the flood wave. However, this would need further investigation of the flood scenario and behavior of the flood wave after breaching.

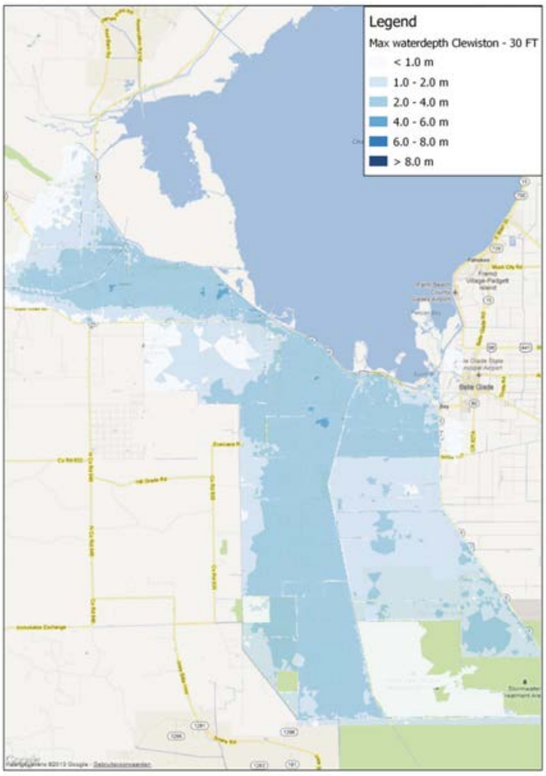



Max water depth [m] – Dam break scenario 20 FT near Clewiston (location 2)

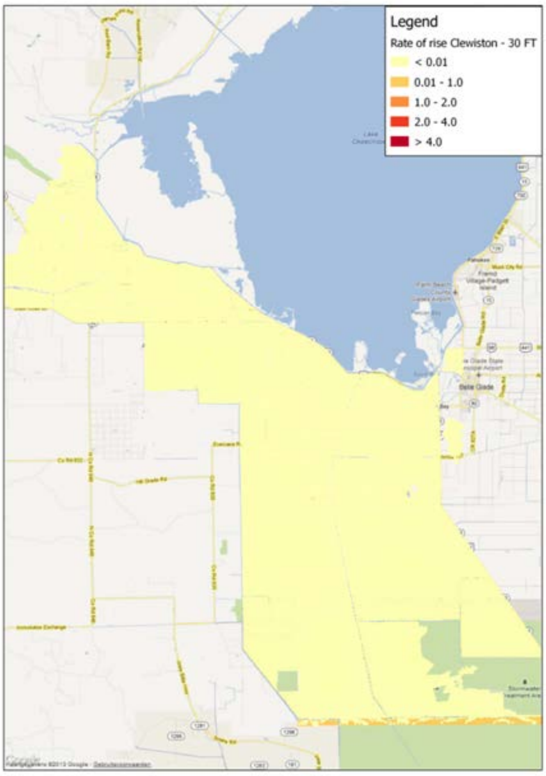



Rate of rise [m/hr] – Dam break scenario 20 FT near Clewiston (location 2)

Figure 58: Flood scenario Clewiston with lake Okeechobee at 20 feet.



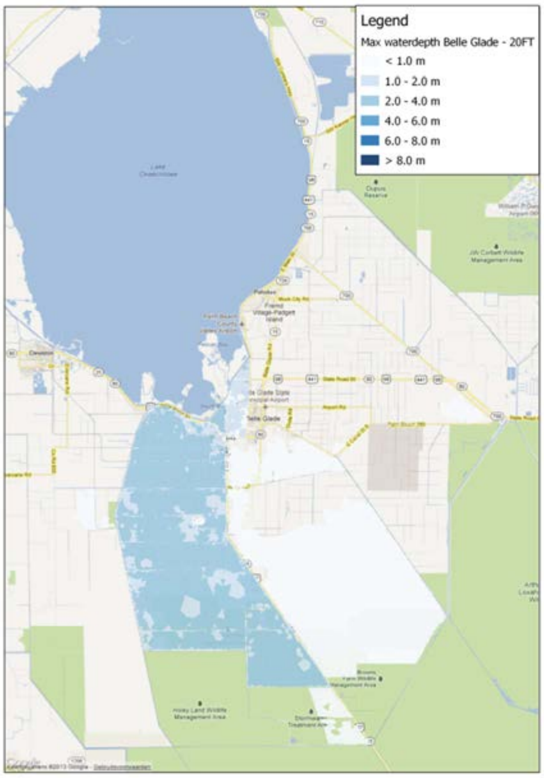

Max water depth [m] – Dam break scenario 30 FT near Clewiston (location 2)



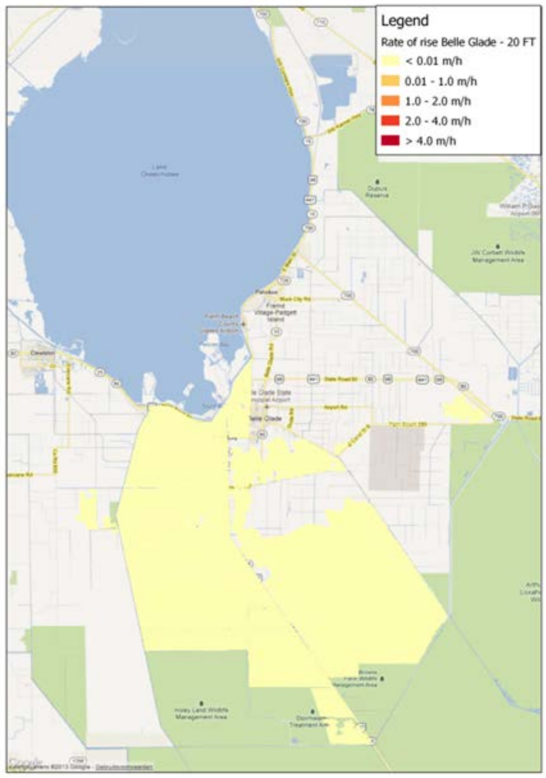

Rate of rise [m/hr] – Dam break scenario 30 FT near Clewiston (location 2)

**Figure 59: Flood scenario North West Sacramento River.**

The following two figures show the flood scenarios for the Belle Glade area. Also in these scenarios the big difference is the flooded area in the 30 feet scenario the flooded area is significantly larger. The maximum water depth near the city of Belle Glade is approximately 4 meters. In both scenarios the rise rates are relatively small, less than 0.01 m/hr, as well as the flow velocities (not shown). Only for the breach with the 30 ft lake level, there is an area near the breach where velocities are between 1 to 2m/s, but such values will still not lead to building damage.




Max water depth [m] – Dam break scenario 20 FT near Belle Glade (location 3)




Rate of rise [m/hr] – Dam break scenario 20 FT near Belle Glade (location 3)

**Figure 60: Flood scenario North West Sacramento River.**

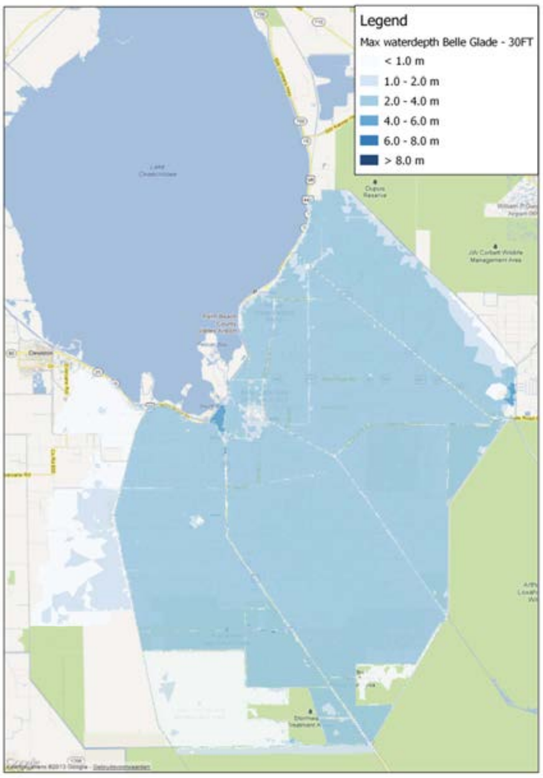
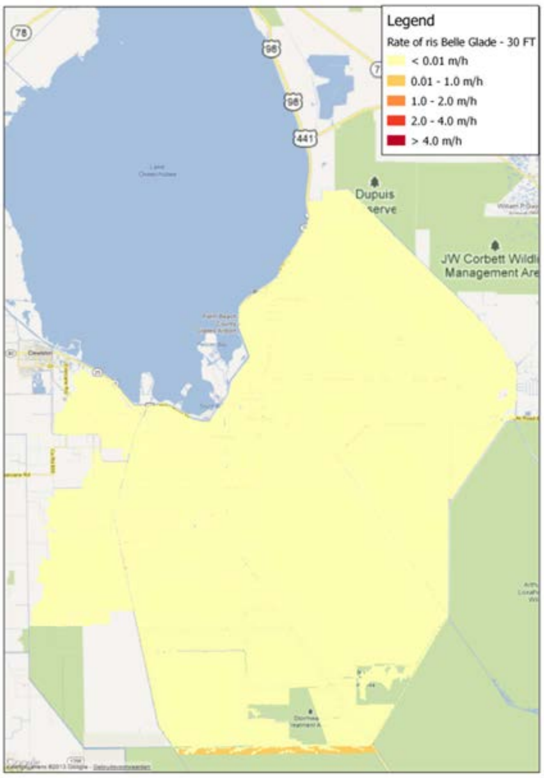
|  |  |
|---|---|
| Max water depth [m] – Dam break scenario 30 FT near Belle Glade (location 3) | Rate of rise [m/hr] – Dam break scenario 30 FT near Belle Glade (location 3) |





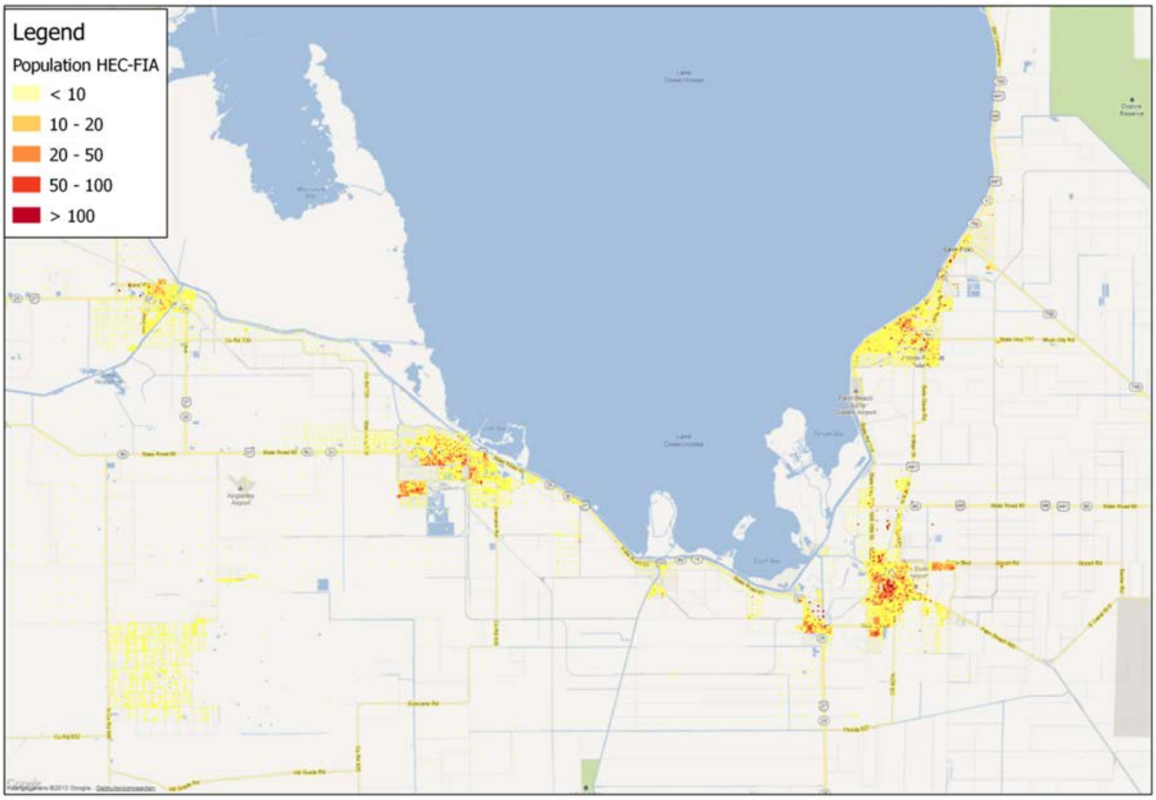
Figure 61: Flood scenario North West Sacramento River.

### 4.2.3 Population data

The population data that is used for this loss of life analysis is provided by USACE. The population data represents the population of the Clewiston and Belle Glade area for the year 2000[14]. In the year 2000, Clewiston had a population of 6,460 and Belle Glade 14,906. The registered population per block group level is distributed over the number of houses in the block group. The number of people that lives in the flood exposed area is approximately 55.000.

In Figure 62 the spatial distribution of the population is shown. The majority of the population is situated in the residential areas of Clewiston en Belle Glade. Only in the southwestern area of the figure there is a concentration of people that is not directly linked to a residential area. This area might be an industrial area with employees.

[14] Night population




Population data based on HEC-FIA for the year 2000.Population data based on HEC-FIA: right plot shows a detailed overview of the highly dense populated area of Sacramento

Figure 62: population data (year 2000).

### 4.2.4 Other assumptions

The following other assumptions are made in the loss of life analysis:

- No preventive evacuation in the loss of life method (interpolated 1953 method and New Orleans method);

- The simulations exclude breaching of secondary embankments (downstream levees, roads, railways, etc.). Thus, overtopping of secondary embankments serves as the only mode of floodwater transfer between compartments.

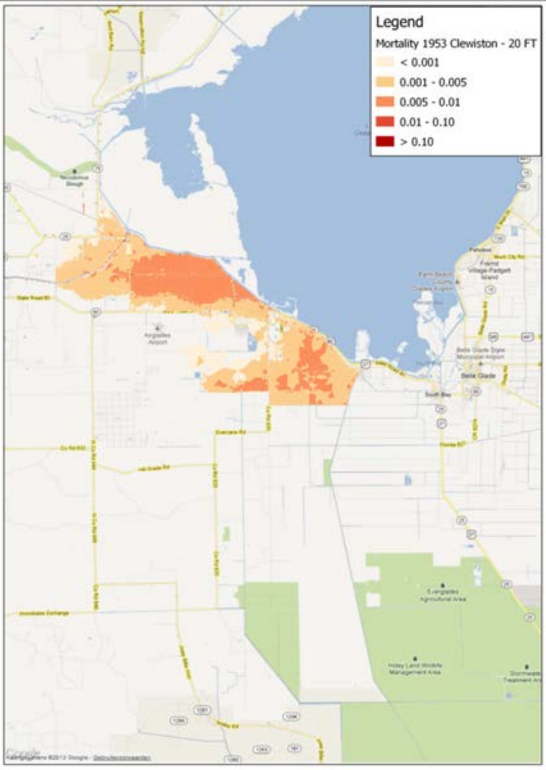
## 4.3 Loss of life

In this section an overview is given of the results of the loss of life analysis with the following four methods: the Interpolated 1953 method (section 4.3.1), the New Orleans method (section 4.3.2), HEC-FIA (section 4.3.34.3.3) and Lifesim (section 4.3.4). The conclusion of this comparison effort is outlined in section 4.3.5.

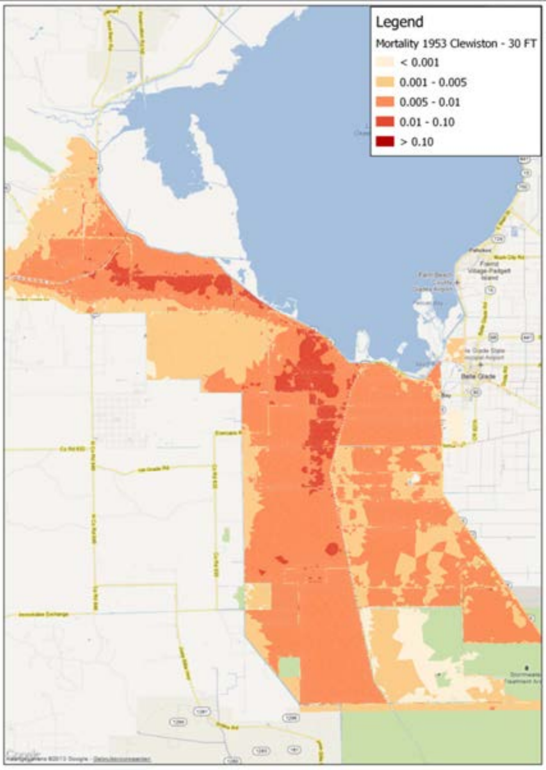
### 4.3.1 Interpolated 1953 method

The rate of rise is the most influential parameter in the mortality functions for the interpolated 1953 method. In a relative sense, the outcomes are more sensitive for the value of the rise rate than for the water depth.

The rise rate for the four different scenarios is relatively small and because of this the mortality rates are determined with the ”remaining zone” mortality function. In general the mortality rate is for all four scenarios between 0.5 and 1 percent. In some areas the mortality rate is higher, between 1 and 10 percent.

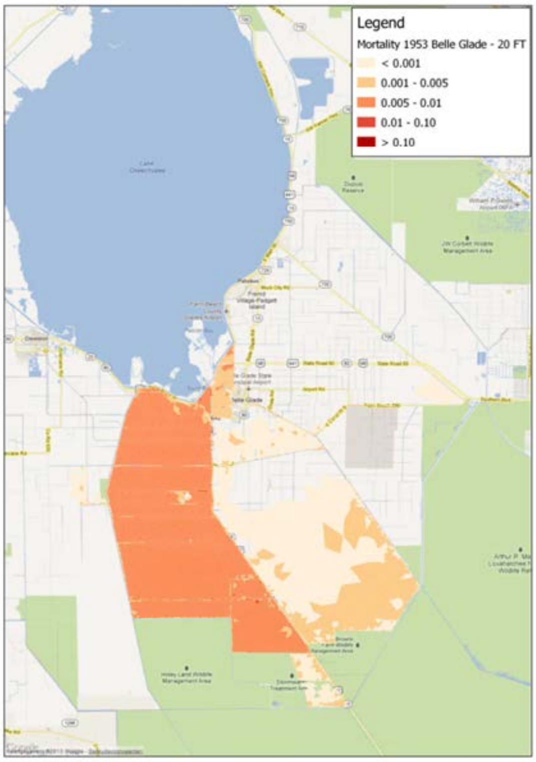



Mortality - Dam break scenario 20 FT near Clewiston (location 2)

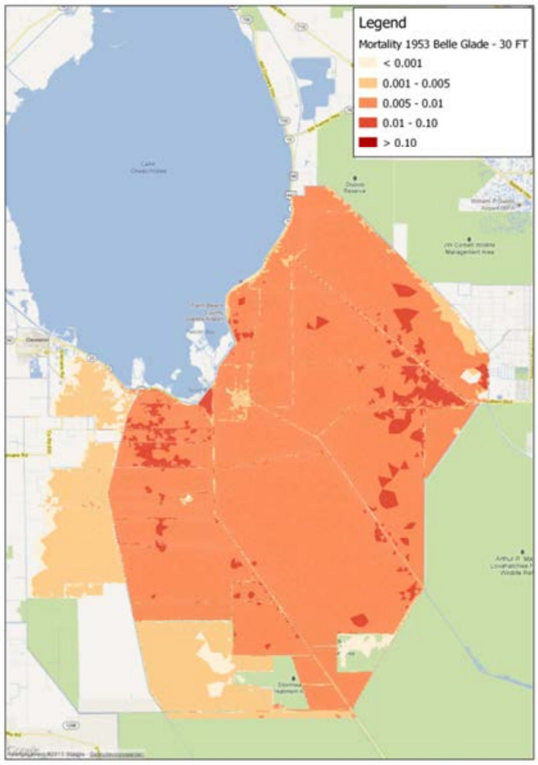



Mortality - Dam break scenario 30 FT near Clewiston (location 2)

**Figure 63: Mortality for the interpolated 1953 functions for the two Clewiston scenarios.**




Mortality - Dam break scenario 20 FT near Belle Glade (location 3)




Mortality - Dam break scenario 30 FT near Belle Glade (location 3)

Figure 64: Mortality for the interpolated 1953 functions for the two Belle Glade scenarios.

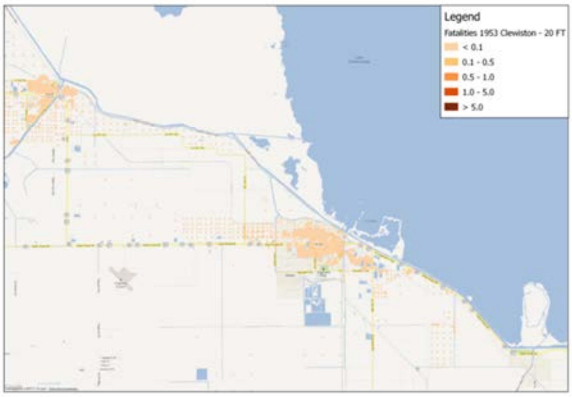
Table 13 shows the results of the loss of life analysis based on the interpolated 1953 method. The difference between the two breach locations is, in terms of number of fatalities, relatively small. The difference in hydraulic load, 30 feet instead of 20 feet, results in an increase of number of fatalities by a factor 5 for the Clewiston breach and a factor 9 for the Belle Glade breach.

| **Interpolated 1953 method** | **Flood Scenario – Overtopping with breach** | | | |
|---|---|---|---|---|
| | Clewiston | | Belle Glade | |
| | 20 FT | 30 FT | 20 FT | 30FT |
| Fatalities – no evacuation[15] | 26 | 118 | 20 | 185 |

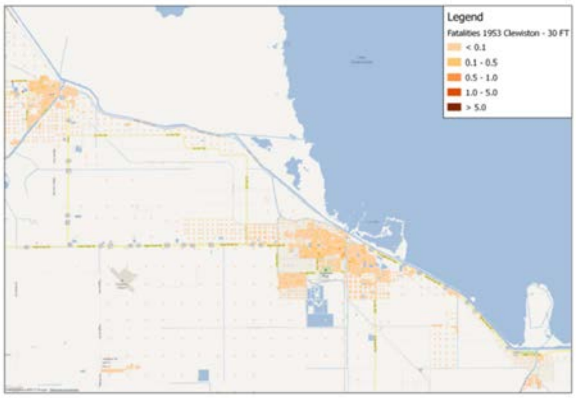
Table 13: Overview number of fatalities (year 2000 population).

The following two figures show a detailed area of Clewiston and Belle Glade with the mortality rates.

[15] Based on the population data of 2000 with totally 55,000 residents.




Fatalities - Dam break scenario 20 FT near Clewiston (location 2)




Fatalities - Dam break scenario 30 FT near Clewiston (location 2)

Figure 65: Mortality for the Clewiston scenarios.


Fatalities - Dam break scenario 20 FT near Belle Glade (location 3)

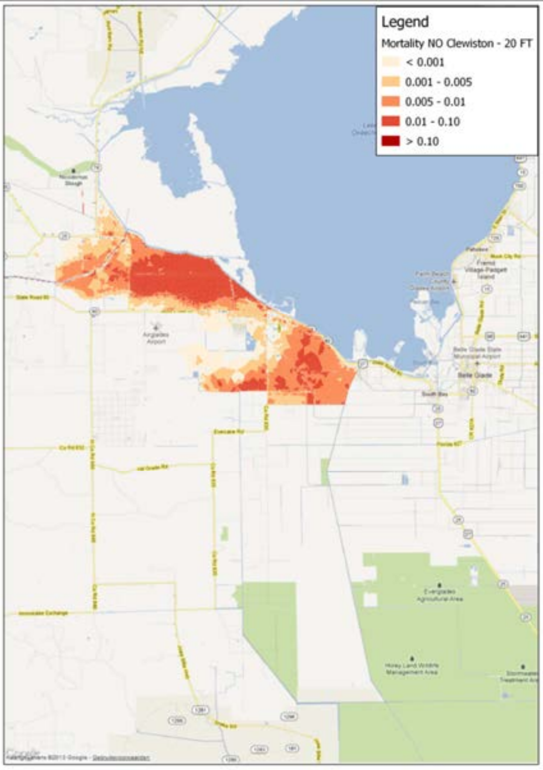

Fatalities - Dam break scenario 30 FT near Belle Glade (location 3)

Figure 66: Mortality for the two Belle Glade scenarios.

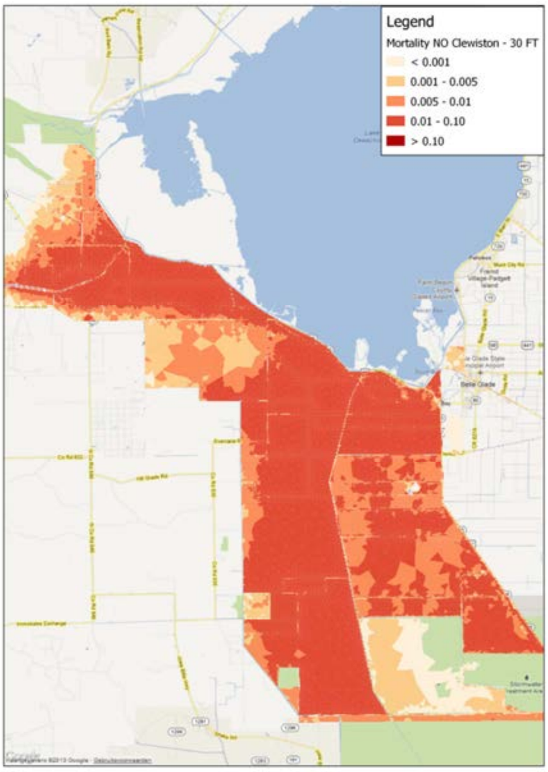
### 4.3.2 New Orleans method

The second method that is used to determine the loss of life for the Herbert Hoover case study is the New Orleans method. The mortality functions of the New Orleans method do not include the effect of the rise rate on the mortality. In the following two figures the mortality rates are shown for the different scenarios.

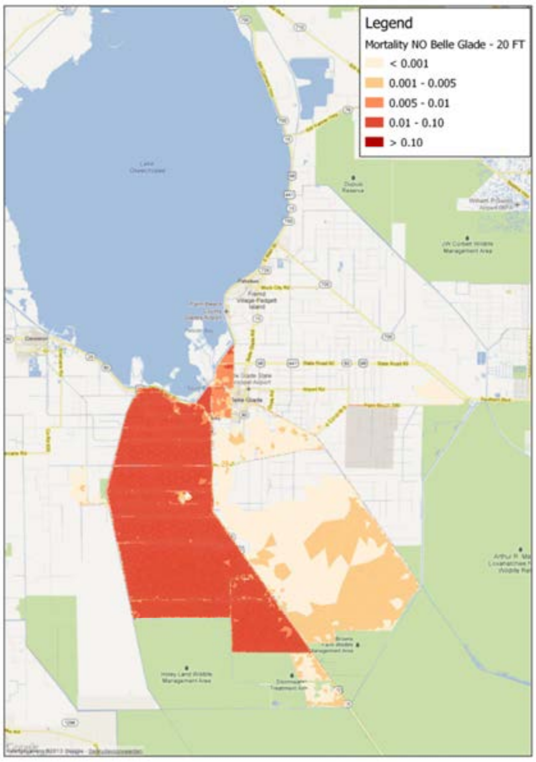
In general the mortality rate is for all four scenarios between 1 and 10 percent.



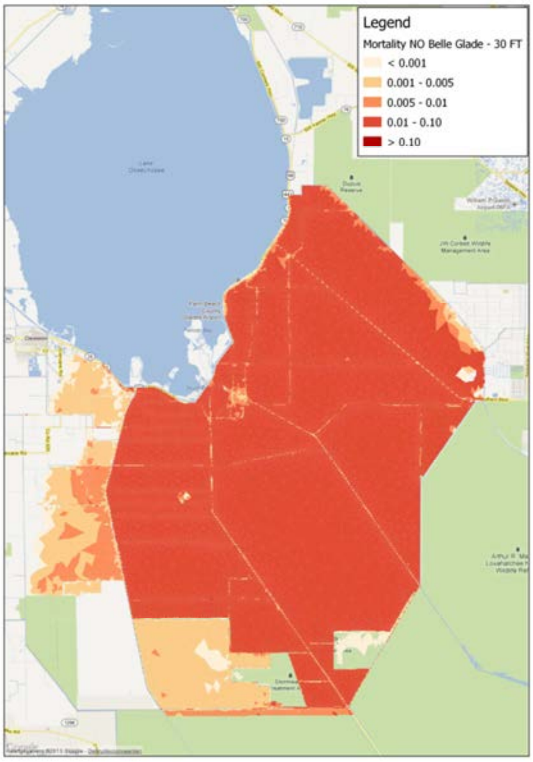

Mortality - Dam break scenario 20 FT near Clewiston (location 2)




Mortality - Dam break scenario 30 FT near Clewiston (location 2)




Mortality - Dam break scenario 20 FT near Belle Glade (location 3)



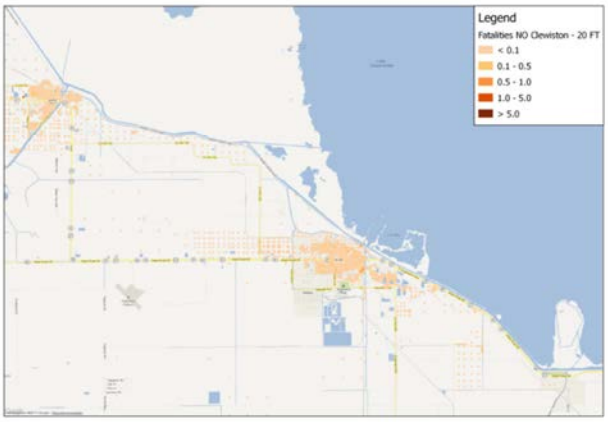

Mortality - Dam break scenario 30 FT near Belle Glade (location 3)

Table 14 shows the results of the loss of life analysis based on the New Orleans method. The difference between the two breach locations is for the 20 feet scenario, in terms of number of fatalities, relatively small. For the 30 feet scenario the Belle Glade scenario the number of fatalities is a factor 1.5 higher compared to the Clewiston scenario. The difference in hydraulic load, 30 feet instead of 20 feet, results in an increase of number of fatalities by a factor 6 for the Clewiston breach and a factor 9 for the Belle Glade breach.

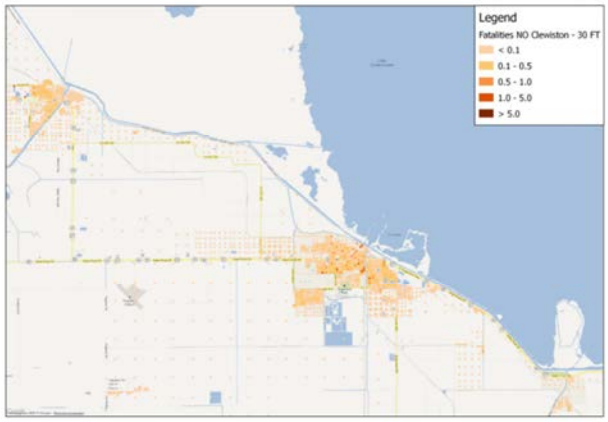
| **Interpolated New Orleans method** | **Flood Scenario – Overtopping with breach** | | | |
|---|---|---|---|---|
| | Clewiston | | Belle Glade | |
| | 20 FT | 30 FT | 20 FT | 30FT |
| Fatalities – no evacuation[16] | 41 | 238 | 40 | 372 |

Table 14: Overview number of fatalities (year 2000 population).

The following two figures show a detailed area of Clewiston and Belle Glade with the mortality rates.




Fatalities - Dam break scenario 20 FT near Clewiston (location 2)

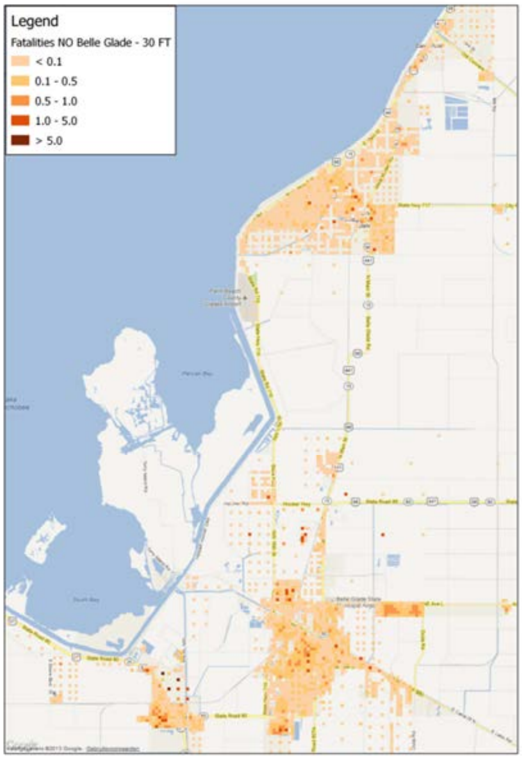



Fatalities - Dam break scenario 30 FT near Clewiston (location 2)

Figure 67: Loss of life for the Clewiston scenarios with the Katrina functions.

16 Based on the population data of 2000 with totally 55,000 residents.


Fatalities - Dam break scenario 20 FT
near Belle Glade (location 3)




Fatalities - Dam break scenario 30 FT
near Belle Glade (location 3)

**Figure 68: Loss of life for the Belle Glade scenarios with the Katrina model.**

### 4.3.3 HEC-FIA

In this section we present the results of the calculations with HEC FIA. Figures * and * below shows the mortality rate for the breach at Clewiston and at Belle Glade. Mortality values are generally low, lower than 1%. Only for the scenario at Clewiston with a 30 ft lake level, some higher mortality values (10% or sometimes higher than 50%) are also found for some locations.


Mortality - Dam break scenario 20 FT
near Clewiston (location 2)


Mortality - Dam break scenario 30 FT
near Clewiston (location 2)

Mortality - Dam break scenario 20 FT near Belle Glade (location 3)

Mortality - Dam break scenario 30 FT near Belle Glade (location 3)

Table 13 shows the life loss for the HEC FIA method. Life loss is generally fairly low, but only for the Clewiston breach with a 30 ft lake level higher life loss values are obtained. This is likely due to the fact that somewhat higher flood depths (between 2 – 4m) are reached, so that higher mortality fractions are found with the stepwise HECFIA function, but this needs further investigation.

| **Interpolated New Orleans method** | **Flood Scenario – Overtopping with breach** | | | |
|---|---|---|---|---|
| | Clewiston | | Belle Glade | |
| | 20 FT | 30 FT | 20 FT | 30FT |
| Fatalities – no evacuation[17] | 11 | 302 | 1 | 7 |

Table 15: Overview number of fatalities (year 2000 population).

Fatalities - Dam break scenario 20 FT near Clewiston (location 2)

Fatalities - Dam break scenario 30 FT near Clewiston (location 2)

Figure *: Loss of life for the Clewiston scenarios with the Katrina functions.

[17] Based on the population data of 2000 with totally 55,000 residents.

| | |
|---|---|
|  |  |
| Fatalities - Dam break scenario 20 FT near Belle Glade (location 3) | Fatalities - Dam break scenario 30 FT near Belle Glade (location 3) |

### 4.3.4 Lifesim

### 4.3.5 Loss of life comparison

In the previous sections 4.3.1 to 4.3.4 the outcomes of the loss of life analysis are reported. In this section a comparison between the outcomes obtained with the various methods is reported. Table 16 compares the life loss estimates for the four methods and the two scenarios.

In the interpolated 1953 method the mortality function includes both the effects of the maximum water depth and rate of rise, whereas the New Orleans method only includes the effect of the maximum water depth on the mortality. Because of this difference and the very low rise rates in the scenarios the number of fatalities is a factor 2 higher for the New Orleans functions compared to the interpolated 1953 functions. For HEC FIA life estimates are fairly low because flood depths are mostly in the lowest mortality category (<4m). Only for the 30 ft lake level breach at Clewiston somewhat higher fatality numbers are obtained.

| Overview loss of life<br><br>Fatalities – no evacuation[18] | Flood Scenario – Overtopping with breach | | | | | |
|---|---|---|---|---|---|---|
| | Clewiston | | | Belle Glade | | |
| | Absolute number of fatalities | | | Absolute value | | |
| | 20 FT | 30 FT | | 20 FT | 30 FT | |
| Interpolated 1953 method | 26 | 118 | | 20 | 185 | |
| New Orleans method | 41 | 238 | | 40 | 372 | |
| HEC-FIA | 11 | 302 | | 1 | 7 | |
| Lifesim | PM | | | PM | | PM |

Table 16: Overview loss of life for all four methods

[18] Based on the population data of 2000 with totally 55,000 residents.

# 5 New Orleans and hurricane Katrina case study

The purpose of this section is to use the data from the loss of life due to hurricane Katrina in New Orleans to compare the different life models and approaches. In the first section (5.1) we present available data on flooding, loss of life and building damage. Section 5.2 shows the results of the application of the different life loss models. The third section (5.3) demonstrates how these models could be utilized to estimate consequences and risks to life for the post-Katrina situation data and assumptions.

### 5.1.1 Flood maps

The flood simulations of overland flow have been made by means of a two dimensional hydraulic model, SOBEK-1D2D developed by WL|Delft Hydraulics. De Bruijn [34] and Maaskant [35] give further background information. The following points summarise the approach used for the flood simulations:

- For terrain height a digital elevation model has made using data from United States Geological Survey (USGS).
- Levee heights and breach locations are based on information provided by the LSU Hurricane Center. This information is based on field observations.
- Only inflow through the main breaches has been considered. Overtopping of levees, the effects of rainfall, drainage canals and pumping have not been considered.
- Breach widths are based on descriptions by IPET (2007) and Seed *et al*. (2006). Based on these reports the growth rate of the breach has been estimated. Inflow discharges through breaches are determined based on the outside water levels reported in (IPET, 2007b) and estimates of the development of the breach profile over time.
- Simulations have been made for the Orleans (de Bruijn, 2006) and St. Bernard (Maaskant, 2007) bowls. No simulations are available for New Orleans East.
- To reduce the calculation time for the St. Bernard bowl only flooding of the residential area is simulated, the wetlands between the 40-Arpent levee and Lake Borgne have not been taken into account.

Given the above assumptions and limitations regarding the input data it is important to realize that these simulations give a first order insight in flood conditions in the affected area, but are not detailed or exact approximations of the flood flow conditions. Information on the water depth, flow velocity, rise rate and arrival time is obtained as output from the simulations. Figures 5 to 9 show the simulated water depth, flow velocity, the product of depth and velocity, rise rate and arrival time of the water for the Orleans and St. Bernard bowls.

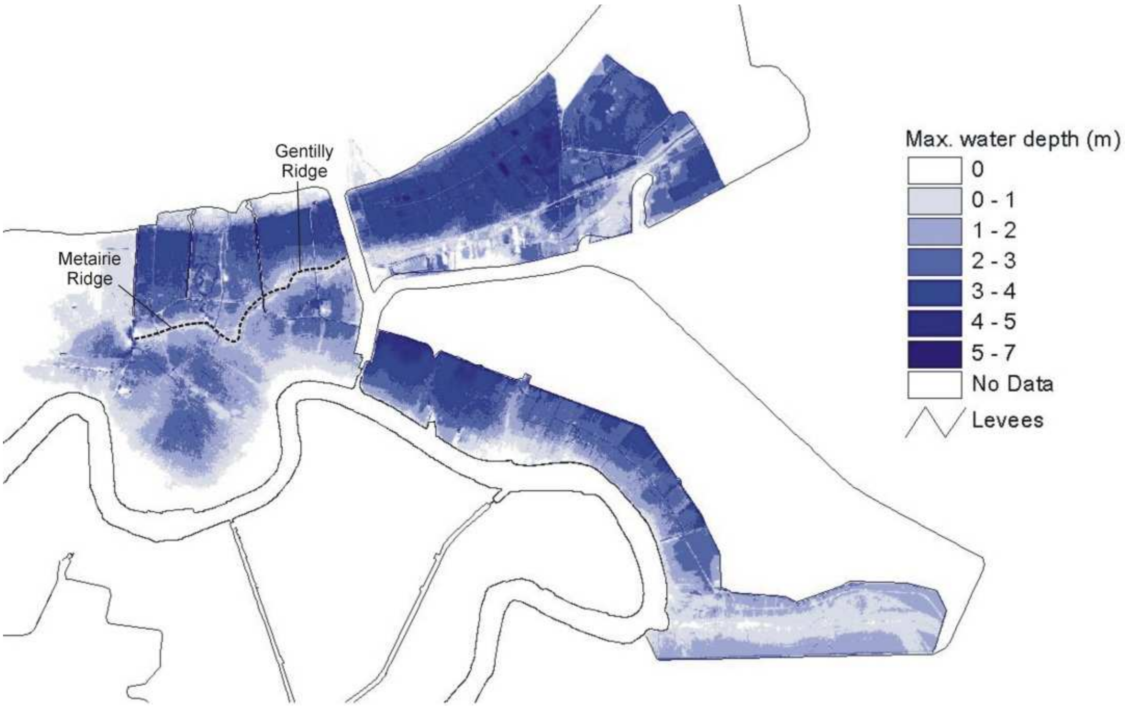



**Figure 69: Maximum water depth. (For the Orleans and St. Bernard bowls it is obtained from simulations. Water depth for the Orleans East bowl is based on the flood depth map provided by the LSU Hurricane Center). (Jonkman et al., 2009)**

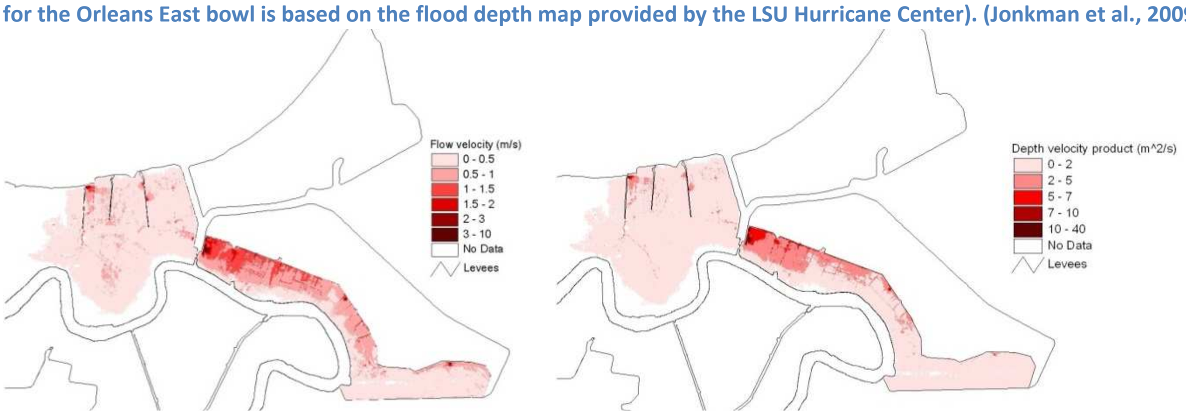



**Figure 70: Maximum flow velocity (left) and product of maximum water depth and maximum flow velocity[19] (hv) (right) for the Orleans and St. Bernard bowls. (Jonkman et al., 2009)**

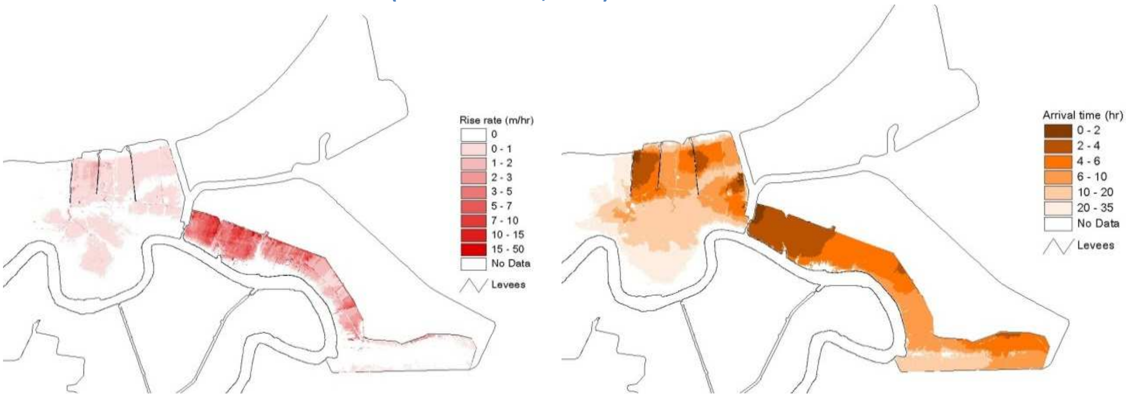



**Figure 71:Rise rate (left) and Arrival time of the water (left) for the Orleans and St. Bernard bowls (Jonkman et al., 2009)**

[19] These results are conservative as maximum values of depth and velocity need not have occurred simultaneously, i.e. $h_{max}v_{max} > (hv)_{max}$.

The simulations show that the most severe conditions occurred in the St. Bernard bowl. Very large flow velocities (3 to 10 m/s) occurred near the catastrophic breaches in the levees along the Industrial Canal. These effects caused destruction in the Lower 9th Ward. Water depths in St. Bernard reached 3 to 4 meters in the deepest parts and rise rates were high (> 5 m/hr) for most of the area.

The Orleans bowl also suffered large water depths. In some locations (especially in the Lakefront area) the water depth was more than 5 meters. However, the flow velocities and rise rates were lower than in St. Bernard. Based on the simulations it is estimated that in the Orleans bowl, only very near the breaches the flow velocities were high (larger than 1 m/s to 2 m/s). For most of the area rise rates were relatively small. The highest rise rates in this area (1 to 2 m/hr) occurred in the northern part. Most of the Orleans bowl flooded within a day. In the middle of the Orleans bowl there are the Gentilly and Metairie ridges that blocked the flow from north to south for some period.

The results of the simulations have been verified with available information regarding flood characteristics, see also (Cunnigham et al., 2006; Maaskant, 2007) for further details. Comparison with the flood depth maps provided by LSU Hurricane Center shows that the flood depth is approximated well for the Orleans bowl (the difference for 90% of the grid cells was smaller than 0,3m (de Bruijn, 2006)). Somewhat larger differences between the simulated depths and the LSU flood maps were found for the st. Bernard Bowl. For the Southeastern part of the bowl the difference exceeded 1m (Maaskant, 2007). Calculated arrival times of the water flow are compared with eyewitness descriptions from (IPET, 2007b) and these show good agreement (on average 20 minutes difference) for the St. Bernard bowl (Maaskant, 2007). For the Orleans bowl the agreement between simulations and eyewitness differs between locations (de Bruijn, 2006), ranging from no almost no deviation in arrival time for locations near the breaches in the London Avenue Canal to several hours for locations in the Southern part of the Orleans bowl. Differences between observations and simulations could be caused by the fact that overtopping of levees and effects of rainfall were not considered in the simulations. In addition, important assumptions that influence the flooding course in the simulations concern the starting time of breaching and the hydraulic roughness of the area.

### 5.1.2 Loss of life dataset

Based on the dataset of deceased victims, the characteristics of Katrina related fatalities, such as age, gender and race are discussed. Data are available for 853 Katrina related fatalities. Information regarding other potentially important factors, such as medical cause of death, activity and behaviour during the hurricane impact, was not available.

**Age**

The age distribution of fatalities is given for 829 fatalities and is presented in Figure 72. Age is unknown for 24 fatalities. The majority of victims were elderly. Out of 829 victims of whom age is known, less than one percent were children and just over fifteen percent were under 51. Older people comprise the majority of the deceased: nearly 85% are older than 51 years, 70% are over 60, and almost half are older than 75 years of age. Population statistics for Orleans and St. Bernard parish[i] show that of the pre-Katrina population about 25% were older than 50, 12% older than 65, and 6% older than 75.

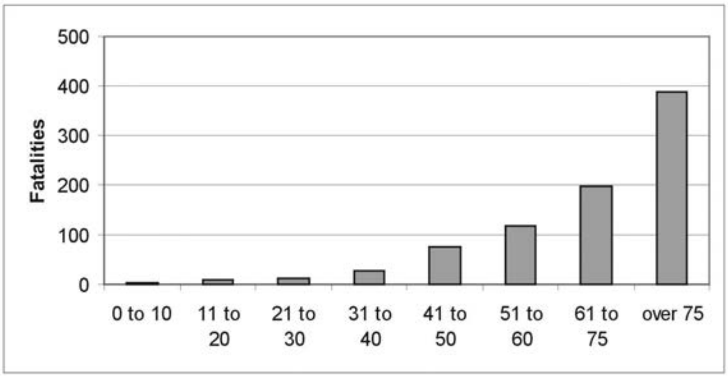


Figure 72: Age distribution of 829 fatalities

A possible explanation of the vulnerability of the elderly is the following. Members of this population group are the most likely to need assistance to evacuate before the storm and are the least capable to survive the physical hazards of the flood (e.g. by moving to higher floors or shelters), the delays before being rescued and the deterioration of basic public health services both inside and outside flooded area. Another factor that could have contributed to the large number of older fatalities in residential areas is that elderly might be less able or willing to evacuate before a hurricane. A past survey (Hurlbert and Beggs, 2004) indicated that there is a slight decline in the evacuation rate with age. However, only very limited information is available for evacuation rates amongst different age groups for Katrina.

**Gender**

The available data do not indicate that gender played a dominant role in Katrina related mortality in Louisiana. For the 853 victims for which gender is known, 432 (50,6%) are male and 421 (49,3%) are female. A general comparison with the gender distribution of the affected population (47,1% males; 52,9% females) shows that males are slightly over represented in the fatality dataset.

**Race**

Of 818 fatalities for which race is listed, 451 (55%) are African American and 334 (40%) are Caucasian (white). Of the others, 18 (2%) victims are listed as Hispanic, 6 (1%) are listed as Asian-Pacific, 4 (<1%) are listed as Native American, and 5 (< 1%) are listed as Other. The race of 35 victims was unknown. In general terms this distribution is similar to the racial distribution of the affected population.

**Type of recovery locations**

The dataset of recovery locations provides information regarding the type of location where the body was recovered for 746 victims, see Table 17. The majority of victims (53%) were recovered from individual residences. Fieldwork shows that many of the residential recovery locations were single story homes that were either not elevated or elevated less than three feet. Medical locations, such as hospitals and medical centers, comprise 147 (20%) of the recovery locations and nursing homes make up 76 (10%) of the recovery locations. The rest of the recovery locations are given in Table 17.

| Location type | Fatalities | |
|---|---|---|
| Residence | 404 | 54% |
| Medical | 147 | 20% |
| Nursing home | 76 | 10% |

| | | |
|---|---|---|
| Open / street | 54 | 7% |
| Morgue / coroner's office / funeral home | 39 | 5% |
| Public shelter | 26 | 3% |
| Public building | 20 | 3% |
| Total | 746 | |

Table 17: Recovered victims from the dataset of recovery locations by location type

**Spatial distribution of recoveries**

The majority of victims were recovered from parishes that suffered the direct flood impacts of Katrina, such as Orleans and St. Bernard parishes. In addition, a substantial number of fatalities occurred in parishes that did not suffer the direct impact of Katrina. In total 147 fatalities were recovered outside the flooded area.

Figure 73 gives an overview of the spatial distribution of recoveries in and near the flooded parts of New Orleans. A distinction is made between two categories of fatalities:

1) Recoveries from residential locations such as residences, nursing homes, street locations and public buildings. In these facilities fatalities can often be directly related to the flood effects.
2) Recoveries from medical locations, shelters and morgues / funeral homes. These recovery locations indicate that these fatalities were not directly related to the impacts of floodwaters. For example, while the Superdome was inside the flood zone, the raised sections of this facility protected those sheltering from floodwaters. Similarly, for hospitals in the flooded areas the ground floors were evacuated as part of storm preparations.

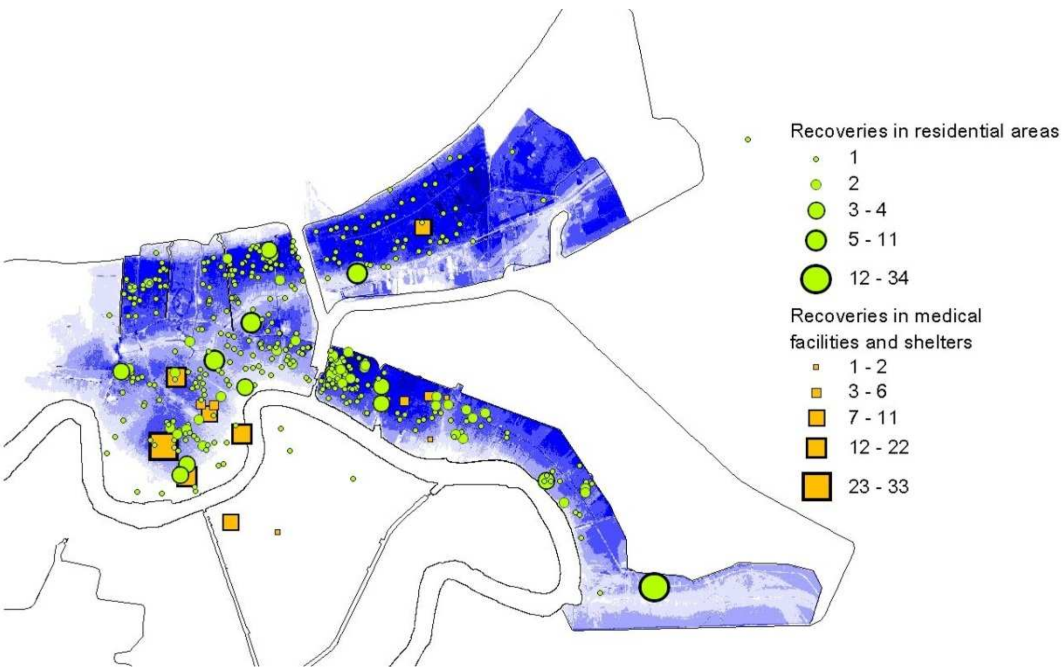



Figure 73: Spatial distribution of the recovery locations of the fatalities (Jonkman et al., 2009).

A similar map was published in the Times-Picayune newspaper under the title "Where they were found"[ii]. Although many of the recovery locations shown in that article correspond to the map below, it differs for a substantial number of recovery locations.

### 5.1.3 Building damage dataset[20]

A dataset with information on damage to residential buildings was created by the City of New Orleans in order to better serve the public and enhance the recovery process from the damage that the hurricane Katrina caused. This information was made available at the CNOGIS, the City of New Orleans GIS Data sharing portal (http://gisweb.cityofno.com/cnogis/dataportal.aspx, accessed in March 2008). The data from this source was compiled into an independent GIS dataset by using ArcView 9.1 and ArcView 9.2 geocoder with StreetMaps USA. The damage dataset contains information for approximately 95,000 residential buildings in Orleans parish. Information for other areas and parishes in Louisiana that were affected by Katrina was not included.

Since the focus of the damage analysis was on single-family residential buildings, the damage dataset includes the following information for every property: location (street address, census block id, neighborhood, zip code, planning district, xy coordinates) and the estimated damage percentage. In the original dataset there is no available information on the building or structure type for individual properties.

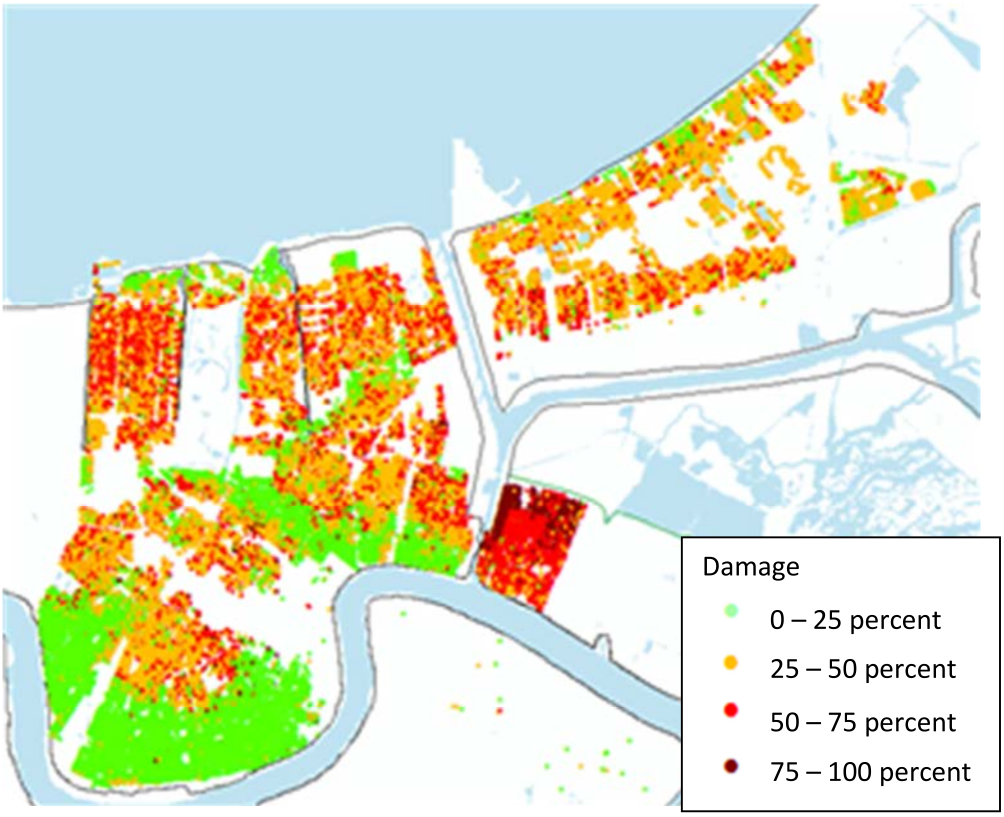



Figure 74: Building damage dataset for Orleans.

**Overview of the dataset**

In order to identify what the housing damage estimates represent and how the damage estimates were determined, available published documentation were reviewed made available by the City of New Orleans, as well as official reports from FEMA, the U.S. Department of Homeland and Security and the City's Department of Safety and Permits (FEMA 2006; IPET 2007; Skinner 2006). According to the available sources, the percent damage estimates are defined as the percentage of pre-Katrina

[20] Pistrika and Jonkman, 2009

building's market value that is damaged, i.e. the ratio of the cost to repair / improve a building to the market value of the building before the disaster:

$$\text{Percentage Damage Value} = \frac{\text{Cost of Repairs}}{\text{Market Value of Building}} \qquad (1)$$

In the remainder of this section the percent damage value is at some locations also indicated as damage fraction, with values between 0 and 1 (i.e. between 0% and 100%). The damage dataset covers Orleans parish and thereby most of the residential properties within Central polder and East polder. For the St. Bernard polder, it covers the neighborhood Lower 9th Ward. Figure 75 gives an overview of the three polders and the average housing damage value by block group. Block groups are spatial units used as standard aggregation levels for the 2000 US Census. On average, block groups cover 0.07 km$^2$ and include 400 houses.

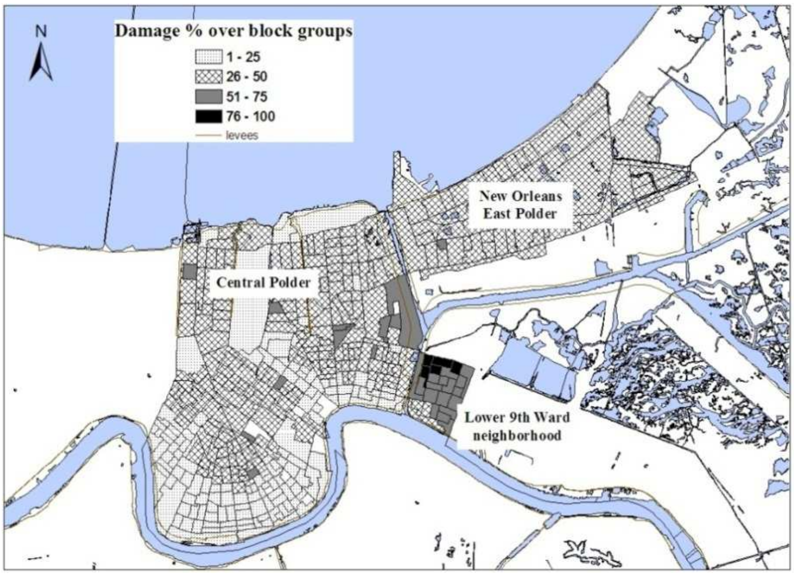



**Figure 75: Damage dataset averaged over block group of the three polders of New Orleans.**

The estimates of damage percentage in the dataset are largely based on direct inspections and surveys of individual residential properties by FEMA contract inspectors to determine eligibility for FEMA housing assistance. For some of the properties impacted by hurricane Katrina, the contract inspectors did not have access to the interiors of the homes, so they conducted damage assessments based on the water lines on the homes' exterior (Skinner 2006). Moreover, remote sensing techniques were used, where site inspections did not take place (Friedland 2009).

The threshold of 50% damage value defines the concept of substantial damage, i.e. the damage sustained by a building whereby the cost of restoring the building to its pre-damaged condition would equal or exceed 50 percent of the market value of the building before the event occurred. Given the method used for damage rating, it is expected that damage percentages lower than 50% mainly indicate damage to the contents of the building, whereas damage values higher than 50% indicate some level of structural damage.

Hurricane Katrina was characterized by both severe flooding and wind effects. It is expected that flood conditions were far more destructive to buildings than wind effects in the City of New Orleans. The Mitigation Assessment Team (MAT) of FEMA found that in inland areas such as New Orleans

wind speeds were lower than the design wind speeds. In these areas some wind damage was common, but typically not as extensive or severe as in areas directly at the coast that were exposed to higher wind speeds (FEMA 2006; Friedland 2009). According to the same report it was the storm surge and subsequent flooding which caused New Orleans' catastrophic level of loss.

## 5.2 Loss of life Model comparison for Katrina

In this section different loss of life methods are applied to the New Orleans Katrina event. Due to the lack of rise rate and velocity data for the New Orleans East bowl the comparison has been made for the New Orleans Metro and the Saint Bernard bowls. Furthermore the analysis has been done on a neighborhood (New Orleans Metro) or tract (St. Bernard) level, in Figure 76 the levels are shown.

**Figure 76: Overview of the neighborhoods and tracts for the New Orleans residential area.**

Based on the derived flood maps, section 5.2.1, the mean flood depth, rise rate and flow velocity are derived, also the number of people per neighborhood/tract is available to determine loss of life.

### 5.2.1 Katrina mortality curves

The derived mortality functions for the flooding of New Orleans are described in section 2.2.2. When this approach is applied to the neighborhoods and tracts in the Orleans and St. Bernard bowls the estimated number of fatalities is 395, while the actual observed number for the considered locations is 404. The accuracy of the approximation by the New Orleans functions is, as expected, very high because the mortality functions are derived based on the Katrina case. In the following two figures the spatial distribution of the observed number of fatalities and the estimated number of fatalities is shown. The spatial distribution patterns are very similar.

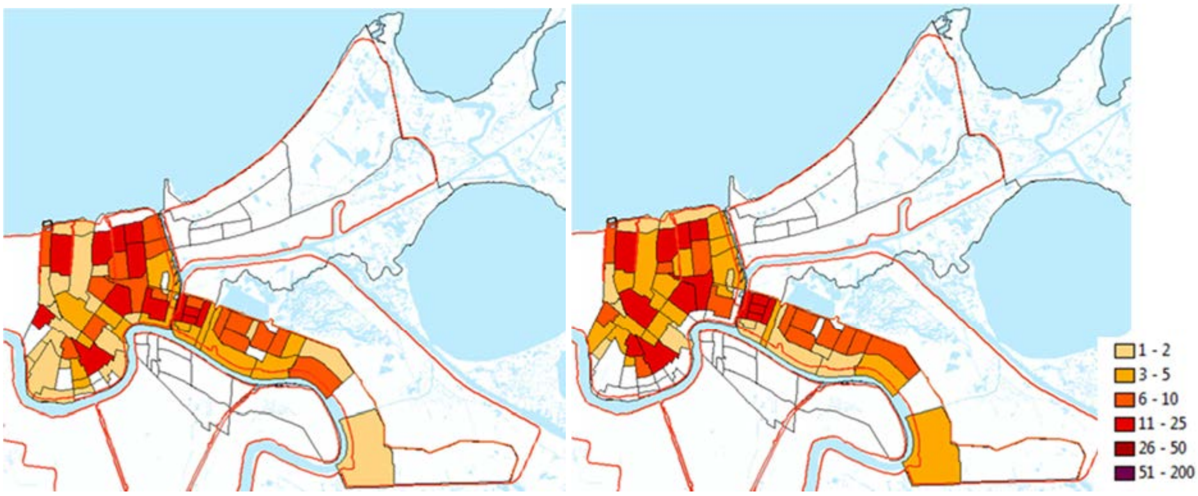



Figure 77: Number of fatalities per neighborhood for the New Orleans Katrina event (left) and the calculated number of fatalities with the New Orleans functions (right).

The following figure shows the comparison between the number of fatalities per blockgroup for the observed number of fatalities and the predicted number by the New Orleans mortality functions. As expected the mortality function derived from the New Orleans data predicts the number of fatalities relatively well.

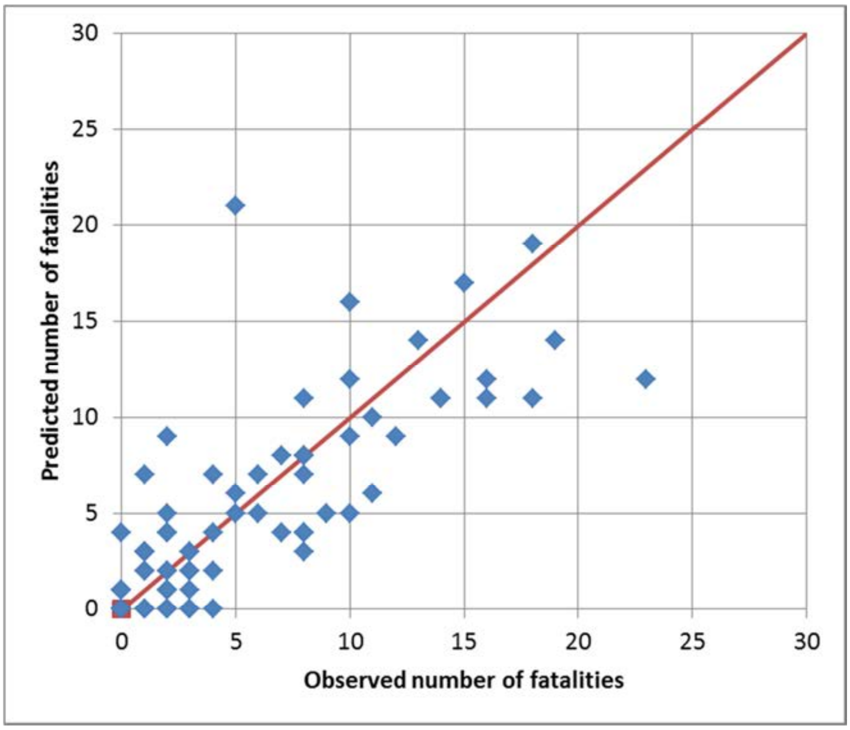



Figure 78: Comparison of the predicted and the observed number of fatalities per blockgroup..

### 5.2.2 Interpolated 1953 curves

The interpolated 1953 curves include one more flood characteristic compared to the Katrina mortality curves, the rise rate. The derivation of the mortality curves is described in section 2.2.1. When the mortality curves are applied to the New Orleans neighborhoods and tracts the estimated loss of life is approximately 760. This is almost double the number of recoveries in the Katrina event. The main reason for this relatively large deviation is the number of fatalities in the Lower Ninth

Ward. Rise rates are relatively high, causing large number of fatalities in that area using the 1953 functions. When we exclude that area from the analysis the number of fatalities in the Katrina event was 340 and the approximated with the 1953 interpolated curves is 415.

| | Katrina event | 1953 interpolated |
|---|---|---|
| New Orleans (all) | 415 | 760 (+83%) |
| New Orleans (excluding 5 tracts in Lower 9th Ward) | 340 | 415 (+22%) |

Table 18: Overview of the loss of life estimations.

The two figures below show the difference in spatial variations in location of the fatalities. The large difference between the Katrina event (left) and the 1953 interpolated curves is in the Saint Bernard bowl caused by the large rise rates in that area.

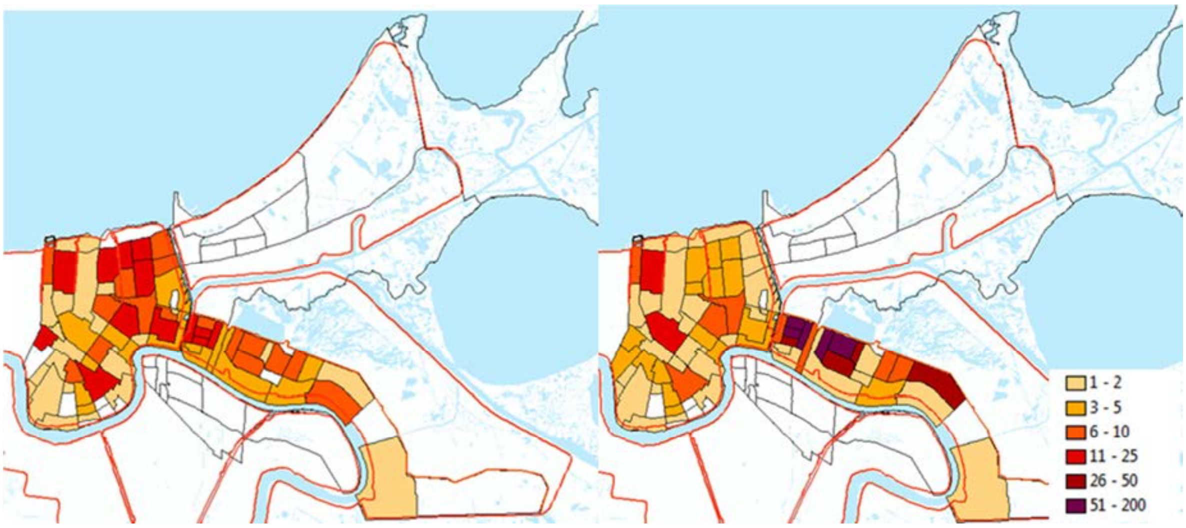



Figure 79: Number of fatalities per neighborhood for the New Orleans Katrina event (left) and the calculated number of fatalities with the interpolated 1953 functions (right).

The following figure shows the comparison between the number of fatalities per blockgroup for the observed number of fatalities and the predicted number by the 1953 interpolated mortality functions. This shows that for several blockgroups the number of fatalities is overestimated by the 1953 mortality functions, this is due to the impact of the rise rate.

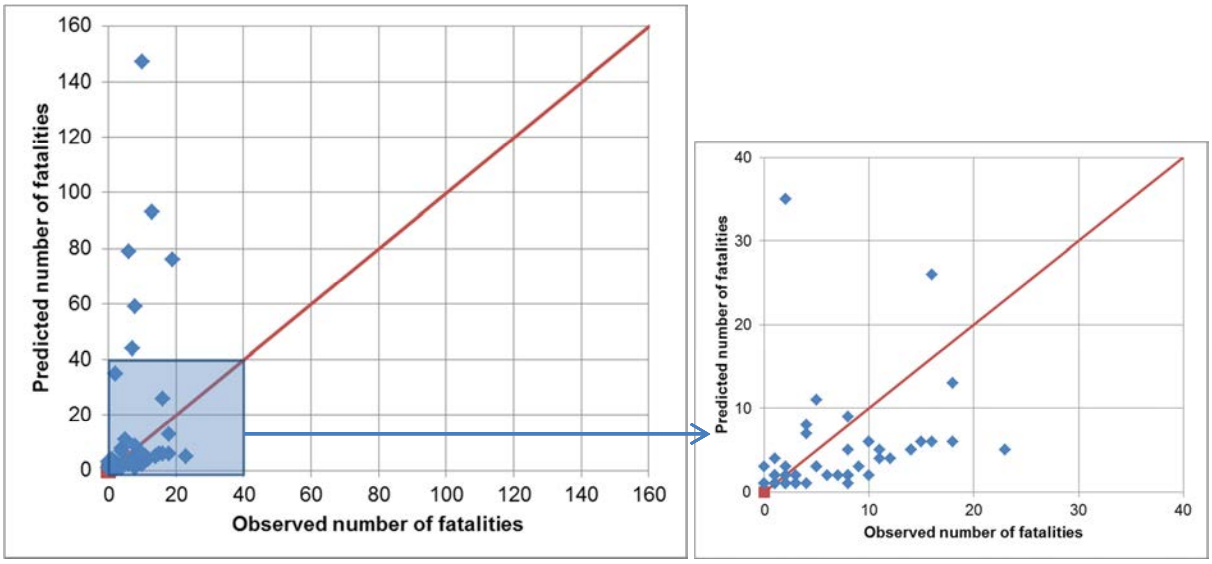



**Figure 80: Comparison of the predicted and the observed number of fatalities per blockgroup, the right figure shows a detailed picture of the blockgroups with a maximum of 40 fatalities.**

### 5.2.3 Hec FIA results

### 5.2.4 Lifesim

### 5.2.5 Model Comparison with life loss dataset

# 6 Findings and recommendations

## 6.1 Conclusions

### 6.1.1 Methodological findings

There are several differences in the methods for loss of life estimation used in the Netherlands and the HEC FIA and Lifesim methods applied in the US.

- Both approaches use relationships between the mortality and flood conditions (esp. water depth). Whereas continuous functions are used in the Netherlands, a stepwise function is used in the US. The mortality rates in the stepwise function are lower than the Dutch functions for lower water depths (<4m), but much higher for higher water depths. If scenarios with high water depths are considered (e.g. NAtomas) HEC FIA gives higher estimates than the other models. If scenarios with lower water depths (e.g. Herbert Hoover Dike) fatality numbers are lower. Overall, if no evacuation is assumed HEC FIA is much more sensitive to differences water depths (see findings for cases below as well).
- Within the Dutch method the functions are applied to all people exposed in a flooded area (irrespective of their state). For a given set of hydraulic conditions, the mortality function determines mortality. In the US method mortality is related to a large extent to the type of state or structure in which people are present (i.e. in a house, or on the road). For a given set of hydraulic conditions, the distribution over buildings and states determine mortality.
- Dutch methods are mostly applicable to larger areas and "average" out differences between states. The methods used in the US are aiming to capture more local processes and effects.
- Within the Dutch method, so called breach zones are included, but for most considered levee breaches, the breach zone is relatively small when compared with the overall affected area. Therefore the breach zone has a limited effect on life loss.

For analysis of evacuation there are also several differences:

- In the US, mostly micro-scale dynamic modelling is used. In the Netherlands macro scale modelling is used assuming a constant driving velocity. The assumption of such a (low) constant velocity may be too pessimistic for cases where sufficient exit capacity is available. In this cases application of dynamic model could provide further insight. However, various model inputs are needed and several input and model uncertainties could be associated with such a dynamic model.
- In consequence and risk studies in the Netherlands preventive evacuation (before breaching) is considered. In the US evacuation is analysed until the arrival of floodwaters (at a certain location). During an actual emergency several uncertainties (e.g. warning, location of breaching) and environmental conditions (e.g. weather) could affect evacuation success.
- In the US interaction between the evacuation process and floodwater movement is included. The question is whether this assumed / programmed type of interaction and driver behaviour will occur during real emergencies.
- Also, there are different definitions of safe zones. In the Netherlands locations outside the area at risk or high grounds are considered safe zones. In the US within HEC FIA safe zones are locations with less than 2 ft of water (within affected area).

- Comparison of warning and mobilization curves used in the Netherlands and the US shows that generally faster mobilization and warning is assumed than in the Netherlands. However, the warning and mobilization does not need to be an important variable in the eventual evacuation time.

### 6.1.2 Findings from the case studies

The various methods have been applied to a number of case studies.

- For the Natomas Basin the life loss depends on the breach location and flood characteristics. The life loss ranged from 900 (interpolated 1953), 2800 (Katrina) and 18,000 (HEC FIA) for a breach in the northwest of the area. The interpolated 1953 method is sensitive for the rise rate, whereas does not affect the Katrina function.
- For the large water depths in the south of the area (>5m) HEC FIA results in very high mortality rates (90%) and life loss. These are higher than the mortality rates obtained with the Dutch models which are in the range of 2 – 8%.
- A breach in the southern part of the basin still results in large water depths in the populated areas (3 – 5m). HEC FIA leads to larger mortality rates and life loss totals than the two Dutch methods.
- For the Natomas Basin the population has grown from about 40,000 people in the year 2000 to almost 100,000 people in the current situation. Depending on the scenario, the life loss has increased by a factor 2.5 to 3. It is expected that required evacuation times will also increase with population growth.
- The required evacuation time has been analysed for the Natomas Basin by means of Dutch methods. Depending on modelling assumptions and evacuation efficiency the required time for evacuation for the basin ranges between 7 hours and more than 24 hours. Since there are many uncertainties in the evacuation process, it is of added value to show the bandwidth in outcomes of various evacuation scenarios. More in general, it appeared to be of added value to show ranges in outcomes for different event scenarios (breaching, water levels, response, day / night).
- Vertical evacuation could be an interesting strategy to reduce life loss, but for Natomas many of the roof tops are below expected flood water level.

For the Herbert Hoover Dike the following is found:

- For this case rise rates and flow velocities are low and flood depths are moderate (2-4m). The differences between the models are smaller. HEC FIA gives lower life loss estimates than the Dutch methods, since flood depths are mostly in the lowest mortality category in HEC FIA (<4m).
- The New Orleans function gives the highest mortality and life loss estimates. The 1953 function gives low estimates because rise rates are small.

Overall, the models can be characterized as follows:

- Interpolated 1953: sensitive for rise rate
- Katrina, gradual increase, mainly based on flood depth-only, no effect of rise rate
- HEC FIA, very sensitive for flood depth

- The dataset on loss of life due to Katrina can be used in future work to test how well various models predict such past events. The Katrina functions are based on this event. The interpolated 1953 functions overpredict observed life loss by about 20%.
- It has been shown how flood scenarios and information on levee failure probability can be used to quantify the risk to life. For the Natomas Basin the individual and societal risk have been quantified based on a (very) limited number of scenarios. It is recommended to include more scenarios in future work to come to a more complete risk analysis. These results could provide a basis for risk communication, decision making and prioritization in risk reduction investments and measures.

## 6.2 Recommendations

- For a more complete comparison it is recommended to add a more complete set of model results of HEC FIA and Lifesim to be able to make a more complete comparison. Further investigation of other cases and flood types is considered to see how the models behave in different conditions and cases.
- The comparison effort could be broadened. Other models like the Life Safety Model could be included as part as an international comparison effort.
- The validity of models can be strengthened by showing how well they predict historical events. In this report data for New Orleans has been included. It is recommended to analyse other events, e.g. flooding of Canvey Island (1953), as part of further analysis
- The different models have different components that affect the mortality rate. To which extent rise rate affects loss of life is still a question. It appeared to be important during the 1953 flood in the Netherlands, but it did seem less important in New Orleans.
- For the Dutch models it would be useful to investigate how a stronger link between evacuation and life loss models can be created. Currently, shelter and evacuation management strategies are only included by a (constant) shelter fraction. For the Netherlands, especially for densely populated areas it would be interesting to explore coupled and dynamic modelling principles to link flood progress, evacuation behaviour and structures.
- Given the variety of situations, flood types, and available models and the importance of assumptions and settings chosen by the user, it is recommended to develop national and international guidelines for loss of life modelling and evacuation, and an associated network of experts. The sensitivity of outcomes was demonstrated for the Natomas Basin case where estimated mortality ranged from 2% to 46% (a factor 20) between various models.
- A general issue in loss of life and evacuation modelling is the lack of historical calibration data. It is recommended to investigate how past events (e.g. the flooding of Canvey Island in 1953) and more recent events (e.g. storm Xynthia in France and the tsunami in Japan) could be used to strengthen the empirical basis. It could further investigated how important factors that are currently not included in the life models, e.g. water temperature, could be further included. Further research on such cases could also support the development of guidelines for which models can be used for certain flood types and conditions.

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# 8 Appendices

- Model assumptions, inputs, outputs
- Methodological descriptions (e.g. details about Evacuaid and loss of life functions)

## 8.1 Summary of the interpolated mortality functions based on the 1953 floods in the Netherlands

Breach zone:

$$F_{D,B} = 1 \quad if \quad dv \geq 7m^2/s \quad and \quad v \geq 2m/s$$

Mortality in the zone with rapidly rising waters

$$F_{D,Rise}(d) = \Phi_N\left(\frac{\ln(d) - \mu_N}{\sigma_N}\right)$$

$$\mu_N = 1.46 \qquad \sigma_N = 0.28$$

$$if \quad (d \geq 2.1m \quad and \quad w \geq 4m/hr) \quad and \quad (dv < 7m^2/s \quad or \quad d < 2m/s)$$

Mortality in the transition zone

For rise rates between 0.5 m/hr ≤ w < 4 m/hr the following function is used. ($F_{D,remain}$ refers to the mortality function for the remaing zone below).

$$F_D = F_{D,Remain} + (w - 0.5)\frac{F_{D,Rise} - F_{D,Remain}}{3.5}$$

$$if \quad (d \geq 2.1m \quad and \quad 0.5m/hr \leq w < 4m/hr) \quad and \quad (dv < 7m^2/s \quad or \quad v < 2m/s)$$

Mortality in the remaining zone

For the remaining zone the following function can be applied:

$$F_{D,Remain}(d) = \Phi_N\left(\frac{\ln(d) - \mu_N}{\sigma_N}\right)$$

$$\mu_N = 7.60 \qquad \sigma_N = 2.75$$

$$if \ (w < 0.5m/hr \quad or \quad (w \geq 0.5m/hr \ \ and \ \ d < 2.1m)) \quad and \quad (dv < 7m^2/s \quad or \quad v < 2m/s)$$

The figure below shows which function can be used for certain hydraulic conditions.

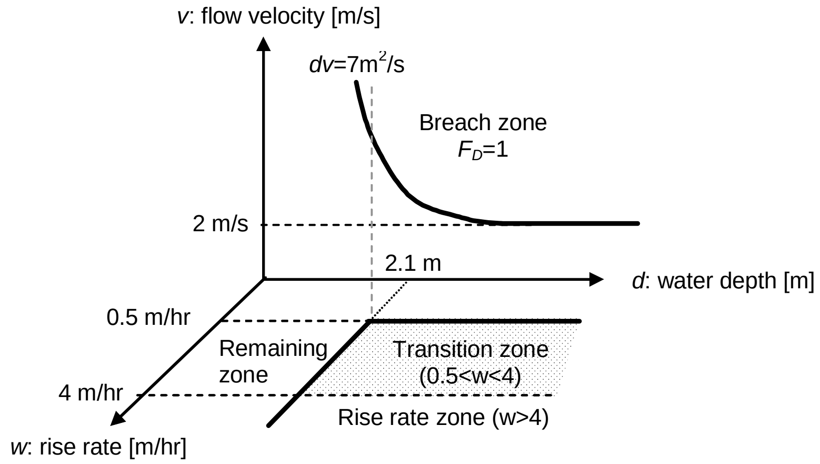


*Figure: Area of application of the various mortality functions as a function of depth, rise rate and flow velocity.*

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1. Data source: Greater New Orleans community data center, http://www.gnocdc.org/, accessed July 2007.
2. http://www.nola.com/katrina/pdf/katrina_dead_122005.pdf, accessed July 2008.